Emergency Data Handbook

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ABSTRACT

When responding to serious emergencies involving the release of radionuclides into the environment, a large quantity and range of information and data will be required in a readily accessible format. This handbook provides a compilation of such information.

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Contents page	Addition of sub-headings.
Page number 51	Figure 10 has been amended to provide greater clarity when it is reproduced in black and white.

December 2003

Page number 44	Table 19(b) has been amended to correct the 'Relevant CFIL' and 'Threshold for exceeding CFIL' values given for ^{241}Pu and ^{241}Am.

June 2006

Page number 63	Figure 13(g) has been amended to correct the logarithmic scale on the ‘Time integrated concentration’ axis (y-axis).

CONTENTS

1 INTRODUCTION

Radiation emergencies occurring within the UK and beyond have the potential to affect the UK environment and its population. Emergencies could occur at fixed nuclear sites such as nuclear power stations, reprocessing facilities or at other premises where large quantities of radioactive materials are utilised. In addition, radioactive sources and material are frequently transported between premises, which presents the potential for radiation accidents occurring during transport.

When responding to emergencies involving the release of radionuclides into the environment, a large quantity and range of information and data will be required in an easily accessible form. This may take the form of generic information on national arrangements for response, accepted dose criteria for implementing countermeasures to protect members of the public, or historical data on past accidents. In addition, information of a more technical nature will be required, such as that necessary for carrying out radiological assessments.

This purpose of this handbook is to provide a compilation of information that may prove useful to staff of the National Radiological Protection Board (NRPB), and other organisations, when involved in the response to a serious radiation emergency. It updates and replaces the previous NRPB Emergency Data Handbook (White, 1986) and NRPB-DL10 (National Radiological Protection Board, 1986) published in 1986.

2 EMERGENCY PLANNING INFORMATION

2.1 Location of nuclear facilities in the UK and Europe

Radiation emergencies at large nuclear sites within the UK have the potential to give rise to radiological consequences for the UK environment and its population. Accidents involving the transport of nuclear or radioactive material may also occur. In general, however, the consequences of transport events are likely to be much less severe. This is primarily because a smaller quantity of radioactive material would be involved in the accident, when compared with a significant accident at a fixed site. Consequently, the spread of radioactive contamination and radiation doses received would be expected to be much smaller.

2.1.1 Location of UK licensed sites

Fixed nuclear sites within the UK encompass a wide variety of premises: some civilian, some military. The most important civilian sites include nuclear power stations, reprocessing facilities and large nuclear research installations. These sites are licensed by the Nuclear Installations Inspectorate (NII) under the Nuclear Installations Act 1965 (Nuclear Installations Act, 1965). The locations of the major nuclear sites in the UK are shown in Figure 1.

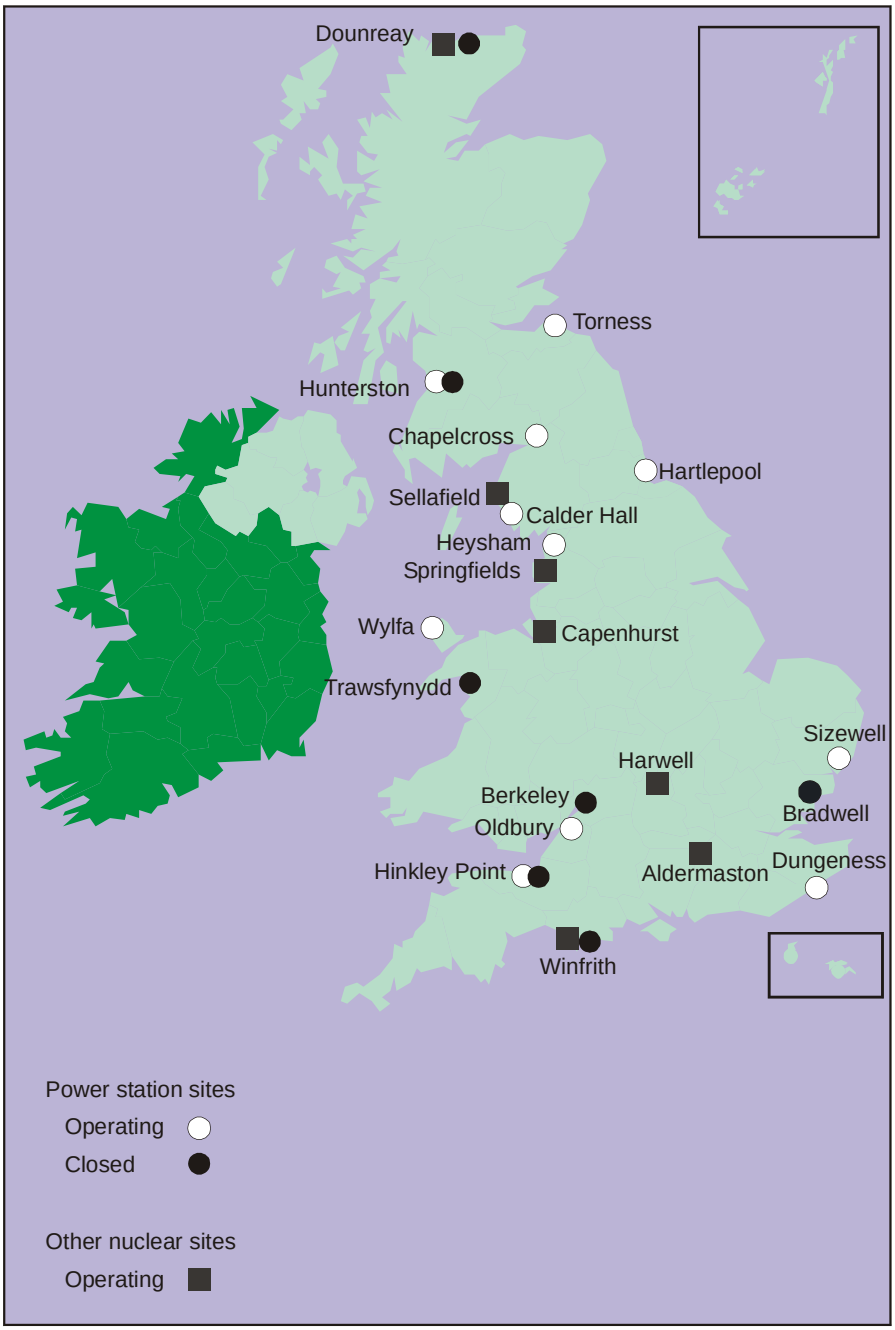


FIGURE 1 Location of UK nuclear licensed sites

2.1.2 Location of nuclear sites within Europe

Radiation emergencies occurring at nuclear sites outside the UK also have the potential to affect the UK environment and its population. The locations of the most significant civilian nuclear plants within Europe are shown in Figure 2.

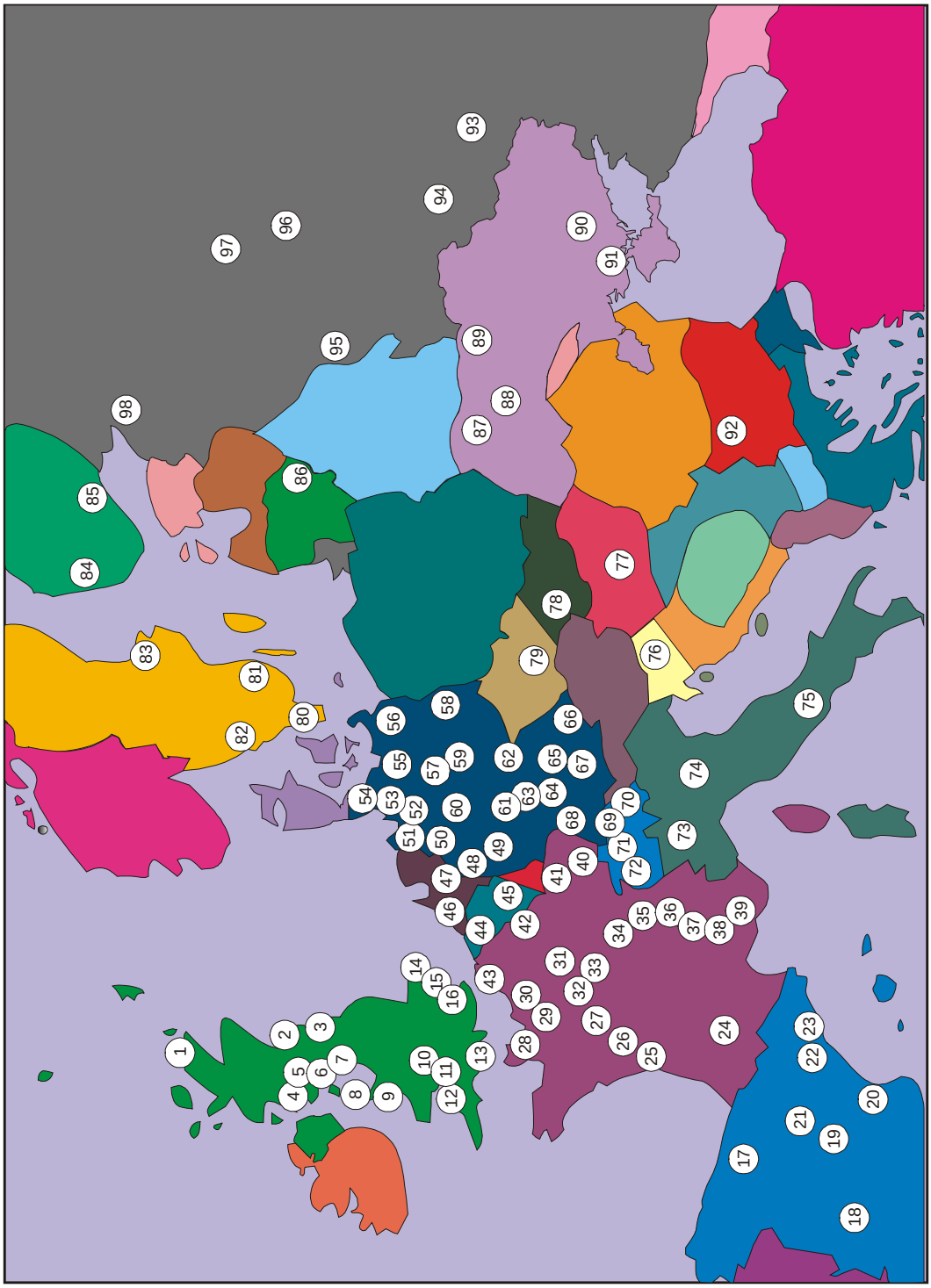


FIGURE 2 Location of European nuclear sites

FIGURE 2 Location of European nuclear plants

GB
United Kingdom
1 Dounreay
2 Torness
3 Hartlepool
4 Hunterston
5 Chapel Cross
6 Calder Hall
7 Heysham
8 Wylfa
9 Trawsfynydd
10 Berkeley
11 Oldbury
12 Hinkley Point
13 Winfrith
14 Sizewell
15 Bradwell
16 Dungeness

ES
Spain
17 Santa Maria de Garona
18 Almaraz
19Jose Cabrera
20 Cotrentes
21 Trillo
22 Vandellos
23 Asco

FR
France
24 Golfech
25 Le Blayais
26 Chinon
27 St Laurent des Eaux
28 Flamanville
29 Paluel
30 Penly
31 Nogent
32 Dampierre
33 Belleville
34 Bugey
35 Creys Malville
36 St Alban
37 Cruas
38 Tricastin
39 Phenix
40 Fessenheim
41 Cattenom
42 Chooz
43 Gravelines

BE
Belgium
44 Doel
45 Tihange

NL
Netherlands
46 Borssels
47 Dodewaard

DE
Germany
48 Jülich
49 Mülheim-Kärlich
50 Emsland
51 Unterweser
52 Stade
53 Brokdorf
54 Brunsbüttel
55 Krümmel
56 Greifswald
57 Grohnde
58 Rheinsberg
59 Wurgassen
60 THTR 300
61 Biblis
62 Grafenrheinfeld
63 Obrigheim
64 Philippsburg
65 Neckarwestheim
66 Har
67 Gundremmingen
68 Karlsruhe

CH
Switzerland
69 Leibstadt
70 Beznau
71 Gosgen-Däniken
72 Muhleberg

IT
Italy
73 Trino Vercellese
74 Caorso
75 Latina

SI
Slovinia
76 Krsko

HU
Hungary
77 Paks

SK
Slovakia
78 Bohunice

CZ
Czech Republic
79 Dukovany

SE
Sweden
80 Bärseback
81 Oskarshamn
82 Ringhals
83 Forsmark

FI
Finland
84 Olkiluoto
85 Loviisa

LT
Lithuania
86 Ignalina

UA
Ukraine
87 Rovno
89 Chernobyl
88 Khmeinitski
90 Zaporozhe
91 South Ukraine

BG
Bulgaria
92 Kozloduy

RU
Russian Federation
93 Novovoronezh
94 Kursk
95 Smolensk
96 Obninskl
97 Kalinin
98 Leningrad

2.2 National arrangements for response within the UK

2.2.1 UK accidents

The types of radiation emergency that are likely to occur within the UK are diverse: ranging from accidents at large fixed nuclear installations that have the potential to affect many thousands of people, to smaller incidents such as a mislaid radioactive source at a university. As a consequence of this potentially wide range of emergency situations the arrangements set up to deal with them are equally diverse.

Under the Ionising Radiation Regulations 1999 (Ionising Radiation Regulations, 1999) 'users' of sources of ionising radiation having the potential to cause a radiation accident are required to develop and maintain appropriate contingency plans for dealing with the consequences of radiation accidents arising as a result of work activities. In addition, the Radiation (Emergency Preparedness and Public Information) Regulations (REPPIR) have incorporated requirements on emergency planning for users (REPPIR, 2001). The main aims of REPPIR have been defined as

(i) To establish a framework for the protection of the public through emergency preparedness for radiation accidents with the potential to affect members of the public, from premises and specified transport operation; and
(ii) To ensure the provision of information to the public.

The road transport of radioactive material within the UK is subject to general legislation in the form of the Ionising Radiation Regulations 1999 and the Radioactive Material (Road Transport) Regulations 1996. National arrangements in support of these regulations and plans also exist and usually follow the generic guidance published by the Home Office in 'Dealing with Disaster' (Home Office, 1997) and guidance from the Scottish Executive in 'Dealing with Disasters together' (Scottish Executive, 2000). A booklet (HSE, 1994), 'Arrangements for responding to nuclear emergencies', has also been published which describes the national arrangements for responding to a nuclear accident arising within the UK. This provides information on the arrangements for response to accidents at fixed sites and those involving radioactive materials in transit. It outlines the role of government departments and national agencies, as well as providing information on the role of local organisations. A group of mainly nuclear-related companies operate a specific plan, RADSAFE (British Energy, 1999), for responding to accidents involving the transport of major consignments of radioactive material by members of the scheme. The transport of nuclear weapons is covered by a Ministry of Defence plan (Ministry of Defence, 2001).

In addition to the national arrangements described above, another scheme is in place: the National Arrangements for Incidents involving Radioactivity (NAIR) (National Radiological Protection Board, 2000). This scheme essentially acts as a 'long-stop' for dealing with unforeseeable, and usually minor, radiation emergencies. NRPB has responsibility for the coordination of these arrangements

which have been designed to provide quick and widely available advice to the police. The NAIR scheme would be invoked for incidents involving radioactivity that may give rise to a public hazard, where no radiation protection expert is otherwise available. In Northern Ireland the Radiation Incidents in a Public Place (RIPP) (Northern Ireland Office, 1996) scheme serves a similar function.

2.2.2 Overseas accidents

Arrangements are also in place for dealing with the consequences on the UK of an overseas nuclear accident. These arrangements are termed the National Response Plan (Department of the Environment, 1993) and are now coordinated by Department for Environment, Food and Rural Affairs. The primary component of the Plan is the national radiation monitoring network and emergency response system known as RIMNET (Radioactive Incident Monitoring Network). RIMNET consists of a fully automated system of about 90 gamma radiation dose rate monitors, sited throughout the UK, which enable increases in radiation levels to be detected. The locations of current RIMNET monitoring sites are shown in Figure 3.

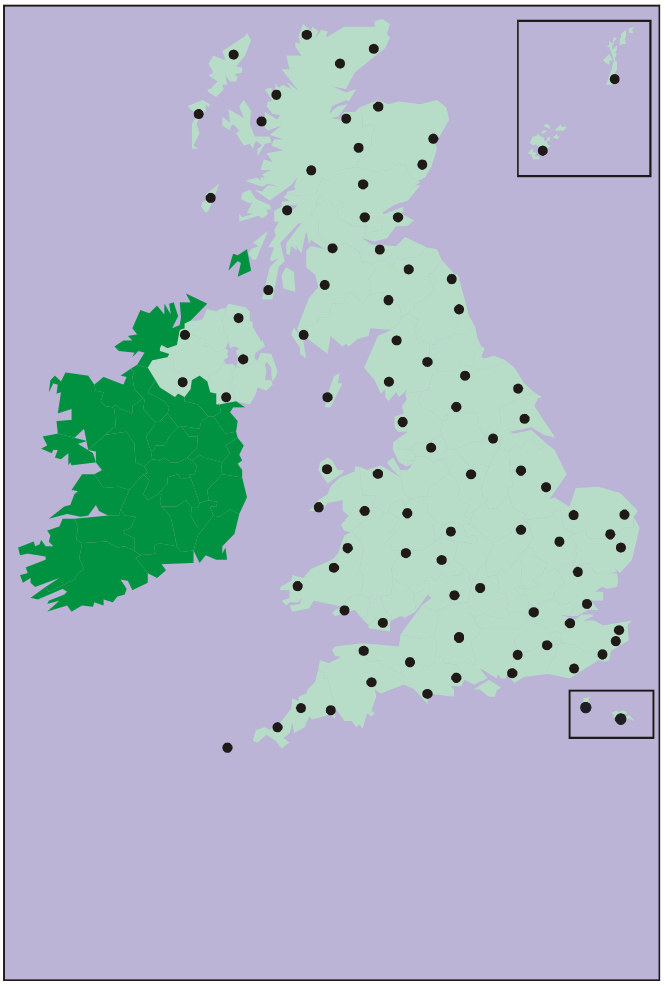


FIGURE 3 Location of RIMNET monitors

2.3 International arrangements for response

2.3.1 IAEA Convention on Early Notification of a Nuclear Accident

This Convention (International Atomic Energy Agency, 1987a) came into force in 1986, subsequent to the accident at Chernobyl. The Convention applies in the event of any accident involving a nuclear facility which has resulted, or may result, in a release of radioactivity to the environment that could be radiologically significant for another state. Notification occurs either directly by the state or through the International Atomic Energy Agency (IAEA). The notification should include information such as the nature of the accident, the time of its occurrence, and its exact location. In addition, the Convention requires that information relevant to minimising the radiological consequences of the accident is also provided. A convention also exists to allow states to request and provide mutual assistance in the event of an emergency (International Atomic Energy Agency, 1987b).

2.3.2 International Nuclear Event Scale (INES)

The International Nuclear Event Scale (International Atomic Energy Agency, 2001) is a means for communicating promptly to the public the safety significance of events reported at nuclear power plants. It was designed by groups from IAEA and the Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD). A summary of the scale and the criteria for each level on the scale are shown in Table 1.

TABLE 1 International Nuclear Event Scale (IAEA, 2001)

Level	Descriptor	Criteria
7	Major accident	External release of a large fraction of the radioactive material in a large facility (eg, the core of a power reactor). This would typically involve mixture of short and long lived radioactive fission products (in quantities radiologically equivalent to more than tens of thousands of terabecquerels of ^{131}I). Such a release would result in the possibility of acute health effects; delayed health effects over a wide area, possibly involving more than one country; long term environmental consequences.
6	Serious accident	External release of radioactive material (in quantities radiologically equivalent to the order of thousands to tens of thousands of terabecquerels of ^{131}I). Such a release would be likely to result in full implementation of countermeasures covered by local emergency plans to limit serious health effects.
5	Accident with off-site risk	External release of radioactive material (in quantities radiologically equivalent to the order of hundreds to thousands of terabecquerels of ^{131}I). Such a release would be likely to result in a partial implementation of countermeasures covered by emergency plans to lessen the likelihood of health effects. Severe damage to the installation. This may involve severe damage to a large fraction of the core of a power reactor, a major criticality accident or a major fire or explosion releasing large quantities of radioactivity within the installation.
4	Accident without significant off-site risk	External release of radioactivity resulting in a dose to the critical group of the order of a few millisieverts.[a] With such a release the need for off-site protective actions generally unlikely, except for local food control. Significant damage to the installation. Such an accident might include damage leading to major on-site recovery problems such as partial core melt in a power reactor and comparable events at non-reactor installations. Irradiation of one or more workers resulting in an overexposure where a high probability of early death occurs.
3	Serious incident	External release of radioactivity resulting in a dose to the critical group of the order of tenths of a millisieverts.[a] With such a release, off-site protective measures may not be needed. On-site events resulting in doses to workers sufficient to cause acute health effects and/or an event resulting in a severe spread of contamination for example a few thousand terabecquerels of activity released in a secondary containment where the material can be returned to a satisfactory storage area. Incidents in which a further failure of safety systems could lead to accident conditions, or a situation in which safety systems would be unable to prevent an accident if certain initiators were to occur.
2	Incident	Incidents with significant failure in safety provisions but with sufficient defence in depth remaining to cope with additional failures. These include events where the actual failures would be rated at level 1, but

TABLE 1 International Nuclear Event Scale (IAEA, 2001)

		which reveal significant additional organisational inadequacies or safety culture deficiencies. An event resulting in a dose to a worker exceeding a statutory annual dose limit and/or an event which leads to the presence of significant quantities of radioactivity in the installation in areas not expected by design and which require corrective action.
1	Anomaly	Anomaly beyond the authorised regime, but with significant defence in depth remaining. This may be due to equipment failure, human error or procedural inadequacies and may occur in any area covered by the scale, eg, plant operation, transport of radioactive material, fuel handling, and waste storage. Examples include: breaches of technical specifications or transport regulations, incidents without direct safety consequences that reveal inadequacies in the organisational system or safety culture, minor defects in pipework beyond the expectations of the surveillance programme.
0	Deviation	Deviations where operational limits and conditions are not exceeded and which are properly managed in accordance with adequate procedures. Examples include: a single random failure in a redundant system discovered during periodic inspections or tests, a planned reactor trip proceeding normally, spurious initiation of protection systems without significant consequences, leakages with the operational limits, minor spreads of contamination within controlled areas without wider implications for safety culture.

[a] The doses are expressed in terms of effective dose equivalent (whole body dose). Those criteria, where appropriate, can also be expressed in terms of corresponding annual effluent discharge limits authorised by national authorities.

3 INTERVENTIONS IN RADIATION EMERGENCIES

3.1 Principles for intervention

In the event of a nuclear emergency that might affect the UK environment and population, interventions may be taken to reduce or limit the radiation dose that might otherwise be received by the public. Such intervention actions in an emergency situation are usually termed countermeasures. The International Commission on Radiological Protection (ICRP) made the distinction between 'practices' and 'interventions' in ICRP Publication 60 (International Commission on Radiological Protection, 1990). Practices are activities that increase exposure to radiation whereas intervention are activities that reduce radiation exposure. Basic principles for intervening in a nuclear emergency, consistent with ICRP recommendations, have been set out by NRPB (National Radiological Protection Board, 1990).

- Countermeasures should only be introduced if they are expected to achieve more good than harm – *justification*.
- The quantitative criteria used for the introduction and withdrawal of countermeasures should be such that the protection of the public is optimised – *optimisation*.
- Serious deterministic health effects should be avoided by introducing countermeasures to keep doses to individuals below the thresholds for these effects.

3.2 Types of countermeasures

Countermeasures appropriate to response after an accident can be divided into three groups: emergency countermeasures; recovery countermeasures; and food and water countermeasures. Emergency countermeasures protect against short-term exposures, recovery countermeasures protect against chronic exposures, and food and water countermeasures are designed to reduce the radiation doses received from consuming food or water that are contaminated with radionuclides.

3.3 Emergency countermeasures

Emergency countermeasures are those that must be taken promptly to be effective. The effectiveness of these countermeasures may be reduced markedly by a delay in their implementation. They are aimed primarily at areas within a few kilometres of the point of release. The countermeasures are intended to provide protection against doses resulting from inhalation of airborne activity and/or external exposure from airborne or deposited activity. Countermeasures which fall into this category include sheltering, evacuation and the administration of stable iodine. In the event of an accident, a combination of countermeasures may be more effective than any single countermeasure.

3.3.1 Sheltering

Sheltering refers to staying indoors with doors and windows closed and ventilation systems turned off. It provides partial protection from external irradiation from airborne and deposited radionuclides and from inhalation of airborne radionuclides. The degree of protection afforded by sheltering depends on the construction of the building and is discussed in Section 5.

3.3.2 Evacuation

Evacuation is the short-term removal of people from an area in order to avoid relatively high radiation doses. The countermeasure is aimed at protecting against external exposure from airborne or deposited radionuclides and from the inhalation of radionuclides. Evacuation can be an extremely effective countermeasure if introduced at an early stage in the emergency.

3.3.3 Stable iodine administration

Administration of stable iodine reduces or prevents the uptake of radioiodine to the thyroid gland, by diluting it with stable isotopes of iodine. The level of protection is maximised if administration can be achieved shortly prior to intake of the radionuclide. Since the administration of stable iodine is most effective if it

is carried out quickly, careful planning of the necessary distribution arrangements is recommended by NRPB (National Radiological Protection Board, 1990).

Stable iodine administration is effective against intakes of radioiodine by inhalation or ingestion. Appropriate restrictions on contaminated food can be used to reduce intakes of radioiodine by ingestion, however, and have the advantage of reducing doses from other radionuclides at the same time. In addition, stable iodine administration is not usually used as a stand-alone countermeasure, since a release containing radioiodine will also result in exposure from external irradiation and may contain other radionuclides that give rise to significant inhalation doses.

Once stable iodine has been administered, it can be assumed that it will be effective for 24 hours (National Radiological Protection Board, 1990). Consequently, for atmospheric releases lasting a few hours, a single intake of stable iodine only is required. If exposure to radioiodine were expected to continue or be repeated for many hours, the duration and uncertainty of the situation would suggest that evacuation should be considered, if this countermeasure had not already been implemented. Repeat administrations of stable iodine would only be considered in exceptional circumstances.

In the UK, the Department of Health has recommended that stable iodine be administered in the form of potassium iodate tablets (Department of Health, 1991). Recommended dosages have also been specified (Department of Health, 1991).

The 2nd UK Working Group on Stable Iodine Prophylaxis has recently published its recommendations in the NRPB Documents Series (National Radiological Protection Board, 2001). NRPB's response to these recommendations was in preparation at the time of publication.

3.3.4 Minor urgent countermeasures

Other urgent countermeasures, notably showering and changing into clean clothes, may be appropriate in the first few hours following a release of radionuclides. Such measures, although prudent and effective against the spread of contamination, are unlikely to lead to significant dose savings.

3.3.5 Dose criteria for urgent countermeasures

The basic principles for intervention in an emergency, outlined in Section 3.1, state that countermeasures should be both justified and optimised. There are a number of factors which would influence any decision on whether or not to implement a particular countermeasure. These factors include the levels of radiation dose saved by the countermeasure, the costs and social impact associated with implementation of the countermeasure, and practical issues such as whether the planned measure can actually be carried out when required. For emergency countermeasures these factors cannot be analysed in detail when an accident occurs, so their assessment is generally carried out as part of the emergency planning process. The result of this planning for intervention is the specification of intervention levels for use in certain situations.

One of the statutory responsibilities of NRPB is to specify emergency reference levels (ERLs) of dose for the implementation of emergency countermeasures to protect the public in the event of a nuclear emergency. ERLs for the emergency countermeasures of sheltering, evacuation and the administration of stable iodine have been published (National Radiologiocal Protection Board, 1990). These generic intervention levels are provided essentially for use by emergency planners and guidance on their use has also been published by NRPB (National Radiological Protection Board, 1997a).

TABLE 2 Recommended ERLs for emergency countermeasures (NRPB, 1990)

Countermeasure	Body/organ	Averted dose (mSv)	
		Lower	Upper
Sheltering	Whole body effective dose	3	30
Evacuation	Whole body effective dose	30	300
Stable iodine	Thyroid	30	300

The advice on ERLs takes the form of ranges of averted dose. A pair of ERLs is given for each type of emergency countermeasure. For averted doses greater than the upper ERL implementation of the countermeasure would almost always be justified, whereas for averted doses less than the lower ERL implementation of the countermeasure would be unlikely to be justified. The ERLs are reproduced in Table 2. ERLs for evacuation and sheltering have also been specified in terms of doses to some individual organs. Following the introduction of the concept of effective dose (International Commission on Radiological Protection, 1990), their use would no longer be expected (National Radiological Protection Board, 1997a).

3.4 Food countermeasures

An accidental release of radionuclides into the environment can result in contamination of the foodchain. The concentrations of radionuclides present in food will vary considerably depending on factors such as the quantity of radionuclides deposited, food and soil type, and agricultural practices. Countermeasures may be implemented to reduce the radiation dose received by the public from consuming contaminated food. The most likely method of reducing doses would be to introduce restrictions on the sale or marketing of specific foods in areas where radionuclide concentrations exceed specified levels. The extent of the area affected by such measures would depend on the pattern and level of deposition, as well as geographical factors and agricultural practices.

The effectiveness of food countermeasures in reducing doses to the public depends on the extent, timing and duration of the countermeasure. In general, peak radionuclide concentrations in milk will occur within a few days for cows grazing on contaminated pasture and will occur immediately for green vegetables subject to direct deposition from the radioactive cloud. Radionuclide concentrations in meat build up more slowly, the peak concentration is usually reached within a few weeks.

In addition to restricting the sale or consumption of foodstuffs in an area, there are other measures which can be taken to reduce the levels of radionuclides present in foodstuffs. Additives, such as Prussian Blue, may be added to animal feed to reduce the availability of radiocaesium. Uncontaminated feed might be introduced to avoid farm animals grazing on contaminated pasture.

3.4.1 Radiological criteria for food restrictions

The European Council (EC) has issued regulations (European Council, 1989a; European Council, 1989b) specifying intervention levels for food contamination which must be applied in the event of any future nuclear accident. They will become legally binding on member states of the European Union following a future accident and will apply to all food marketed. Levels are also specified (European Council, 1990) by the European Council for radionuclides in animal feed. In the UK, these levels are enacted under the Food and Environment Protection Act 1985 (Food and Environment Protection Act, 1985).

The maximum permitted levels, referred to here as Council Food Intervention Levels (CFILs), specified in the regulations, together with notes on their application, are reproduced in Table 3. It should be noted that for each category of food, limits are placed on the concentration of radionuclides in four groups: radioisotopes of iodine, radioisotopes of strontium, alpha-emitting isotopes of plutonium and transplutonium elements, and other radionuclides with half-lives greater than ten days. The limits apply to the sum of the concentrations of radionuclides in each group rather than the level of individual radionuclides falling in each category.

NRPB has recognised the use of these limits for radiological protection purposes (National Radiological Protection Board, 1994) and it is considered unlikely that limits more restrictive than the CFILs could be justified on radiological protection grounds. In certain circumstances, such as a severe accident limiting food supply, higher levels might be justified.

TABLE 3 European Council Food Intervention Levels

Radionuclide	Intervention levels (Bq kg^{-1})				
	Baby foods	Diary produce	Minor foods	Other foods	Liquid foods
Isotopes of strontium, notably ^{90}Sr	75	125	7,500	750	125
Isotopes of iodine, notably ^{131}I	150	500	20,000	2,000	500
Alpha-emitting isotopes of plutonium and transplutonium elements	1	20	800	80	20
All other radionuclides of half-life greater than 10 days, notably ^{134}Cs and $^{137}Cs^{\dagger}$	400	1,000	12,500	1,250	1,000

† This category excludes ^{3}H, ^{14}C and ^{40}K.

3.5 Water countermeasures

Following an accidental release of radionuclides into the environment, radionuclides may deposit directly into sources of drinking water or be deposited on the ground and subsequently transported in groundwater or runoff into water supplies. The large catchment area of water supplies would usually be expected to provide a large degree of dilution of any activity entering a water body. In addition, normal delays between deposition and supply, coupled with the effect of normal water treatment and filtration, would reduce levels of radionuclides observed in water destined for public consumption. Following an accident it is therefore highly unlikely that mains drinking water supplies would become significantly contaminated from airborne releases. The highest doses from consumption of drinking water might be expected to be received by households using contaminated rainwater for drinking.

3.5.1 Radiological criteria for water restrictions

The European Council regulations specify CFILs for radioactive contamination of liquid foods, the definition of which includes bottled water but not normal public drinking water supplies. The regulations state that the CFILs should be applied to mains drinking water at the discretion of competent authorities in member states. Following investigations into the radiological implications of adopting such intervention criteria, NRPB has advised that the CFILs for liquid foods should be adopted as Action Levels for all drinking water supplies in the UK (National Radiological Protection Board, 1994). These are detailed in Table 4.

TABLE 4 Recommended Action Levels for drinking water supplies (NRPB, 1994)

Radionuclide	Action Levels*,† (Bq l^{-1}) liquid foods
Isotopes of strontium, notably ^{90}Sr	125
Isotopes of iodine, notably ^{131}I	500
Alpha-emitting isotopes of plutonium and transplutonium elements	20
All other radionuclides of half-life greater than 10 days, notably radioisotopes of caesium and ruthenium‡	1,000

* These Action Levels refer to all water supplies which are intended, at least in part, for drinking and food preparation purposes.

† It is the sum of the concentrations of all the radionuclides included within a category and detected in the water which should be compared with the Action Level.

‡ This category excludes ^{3}H, ^{14}C and ^{40}K.

3.6 Recovery countermeasures

Once there is no further threat of release and all emergency countermeasures have been implemented, consideration would be given to the implementation of recovery countermeasures. Longer term countermeasures protect against exposure pathways which are likely to persist after the release has ceased. They are generally associated with the longer term environmental distribution of deposited radionuclides and include ingestion of contaminated food and water (considered above), external irradiation from deposited radionuclides, and

inhalation of resuspended radionuclides. There are two types of primary recovery countermeasure: decontamination measures and restricted access. Measures in either category range from simple through to highly disruptive actions. The effectiveness of any measure in reducing dose depends on the measure considered and the characteristics of the environment. Some of the more disruptive measures may have a substantial and long-term impact on the lives of the affected population. Further discussion of this may be found in the NRPB statement on intervention for recovery after accidents (National Radiological Protection Board, 1997).

3.6.1 Decontamination measures

The category described as 'decontamination measures' (National Radiological Protection Board, 1997) is defined very broadly to include any techniques that reduce exposure by treating contaminated areas directly. These include 'true' decontamination techniques, such as the removal of soil or road planing, and those that leave the contamination *in situ*, but reduce the exposure from it, such as covering contaminated surfaces to reduce direct irradiation and applying treatments to prevent resuspension and subsequent inhalation of the radionuclides.

3.6.2 Restricted access measures

Restricted access measures reduce exposure by removing people from areas of contamination or by controlling the time spent in such areas. Such measures may range from preventing or limiting access to localised contaminated areas, through to relocation of the resident population from – and prohibition of all access to – an area for weeks, months or even years until general exposure levels have reduced to acceptable levels.

3.6.3 NRPB guidance on recovery countermeasures

NRPB has issued guidance on the implementation of recovery countermeasures (National Radiological Protection Board, 1997). In the guidance, recovery countermeasures are divided into three categories: according to their effectiveness, impact and time/resource requirements. The categories and examples of countermeasures are shown in Table 5. A summary of the NRPB advice on recovery countermeasures is presented in Table 6.

TABLE 5 Categories of recovery countermeasure (NRPB, 1997)

Category	Description	Likely examples
A	Moderately dose effective, relatively low resource/disruption, prompt implementation, completed within about one month	Ploughing large areas of grass; Grass cutting Extended evacuation/short-term relocation (short-lived radionuclides) Vacuum sweeping/fire hosing all metalled surfaces
B	Dose effective, relatively high resource/disruption, long duration/lasting impact	Turf/soil removal and replacement Double digging all soil/grass areas Road planing Prolonged or permanent relocation
C	Either: poorly dose effective Or: moderately dose effective, high resource/disruption etc	Fire hosing buildings; Sandblasting walls Roof replacement Cleaning indoor surfaces

TABLE 6 Summary of advice on recovery countermeasures (NRPB, 1997)

Circumstance	Countermeasures	
	To consider	Unlikely to be justified
Any off-site contamination	Category A	Category B, C*
Dose > 10 mSv y^{-1}	Category A, B†	Category C‡
Lifetime dose > 1 Sv	All	None

* May be justified in support of other measures.

† Need to offset increasing resource/disruption with increasing dose averted; in general, relocation would not be justified at this level.

‡ May be justified in support of other measures, or if Category B measures impractical.

4 PAST RADIATION ACCIDENTS

Nuclear power has been used in a growing number of countries for approximately 50 years. In a few countries the use of nuclear power has included the development of nuclear weapons but, for most, the generation of electricity in nuclear power stations has been the primary aim. A number of serious accidents have occurred at nuclear facilities which have led to releases of radionuclides into the environment and subsequent improvements in nuclear emergency response both nationally and internationally. In addition, radiological accidents involving other sources, such as satellites and medical radiation sources, have also occurred.

In this section, a synopsis is presented of the some of the major nuclear and radiological accidents that have occurred to date. Seven radiation accidents are outlined: Kyshtym (1957), Windscale (1957), Palomares (1966), COSMOS 954 (1977), Three Mile Island (1979), Goiânia (1987), and Chernobyl (1986). Each accident is described in terms of the type of facility involved, the nature of the accident, the quantities and types of radionuclides released, the resulting radiation doses and countermeasures implemented and, where relevant, the ranking of the accident on the International Nuclear Event Scale (INES).

4.1 Kyshtym

4.1.1 Facility (Romanov, G N *et al*, 1991; Trabalka, J R and Auerbach, S I, 1991)

Kyshtym is a town situated in the Southern Urals of Russia. Located close to the town is Chelyabinsk-40, a military installation which produced materials for nuclear weapons. This facility incorporated a radiochemical plant for extracting plutonium. Heat generating, high level radioactive waste (HLW) was produced in the process and subsequently stored in water-cooled stainless steel tanks on site.

4.1.2 Nature of the accident (Romanov, G N *et al*, 1991; Trabalka, J R and Auerbach, S I, 1991)

On 29 September 1957 one of the steel tanks containing 70–80 tonnes of heat generating HLW exploded, releasing radionuclides into the environment. Precise details of the accident and its cause are not known. The investigating Soviet commission concluded that the most likely cause of the accident was a chemical explosion within a tank of overheated HLW. Corrosion problems and failure of the monitoring equipment had more than likely resulted in the loss of the water-cooling system.

4.1.3 Radionuclides released (Romanov, G N *et al*, 1991; Trabalka, J R and Auerbach, S I, 1991)

A total of 740,000 TBq of mixed fission products has been estimated to have been released, equating to approximately 10% of the total radioactive material in the tank. The radioactive material was released to a height of roughly 1,000 metres and widely dispersed in aerosol form. Deposition from this cloud caused widespread contamination to the north-east of the site, along a path some 300 km long and approximately 20,000 km^2 in area. Estimates of the quantities of individual radionuclides released are shown as ranges in Table 7 and the deposition of ^{90}Sr resulting from the accident is illustrated in Figure 4 (Romanov, G N *et al*, 1991; Trabalka, J R and Auerbach, S I, 1991).

TABLE 7 Radionuclides released in aerosol form during the Kyshtym accident (Romanov, G N *et al*, 1991; Trabalka, J R and Auerbach, S I, 1991)

Radionuclide	Activity released (TBq)
^{89}Sr	0–2,000
^{90}Sr	4,000–5,000
$^{95}Zr/^{95}Nb$	16,000–18,000
^{106}Ru	3,000
^{137}Cs	30–700
^{144}Ce	50,000

4.1.4 Radiation doses and countermeasures (Romanov, G N *et al*, 1991; Trabalka, J R and Auerbach, S I, 1991)

Initial dose rates within 100 m of the release point exceeded 4 Gy h^{-1} falling to 30 mGy h^{-1} at 3 km. Doses to members of the public in the first year arose principally from ^{144}Ce + ^{144}Pr (beta doses) and ^{95}Zr + ^{95}Nb (gamma doses), while longer term doses were dominated by ^{90}Sr. Nearly 11,000 people were relocated from 23 locations in a 700 km^2 area where contamination of ^{90}Sr exceeded 0.1 MBq m^{-2}. Approximately one-quarter of this area remained uninhabited until at least 1990. Agricultural restrictions were also applied in the affected area. No complete estimates are available of the collective dose to the local population arising from this accident.

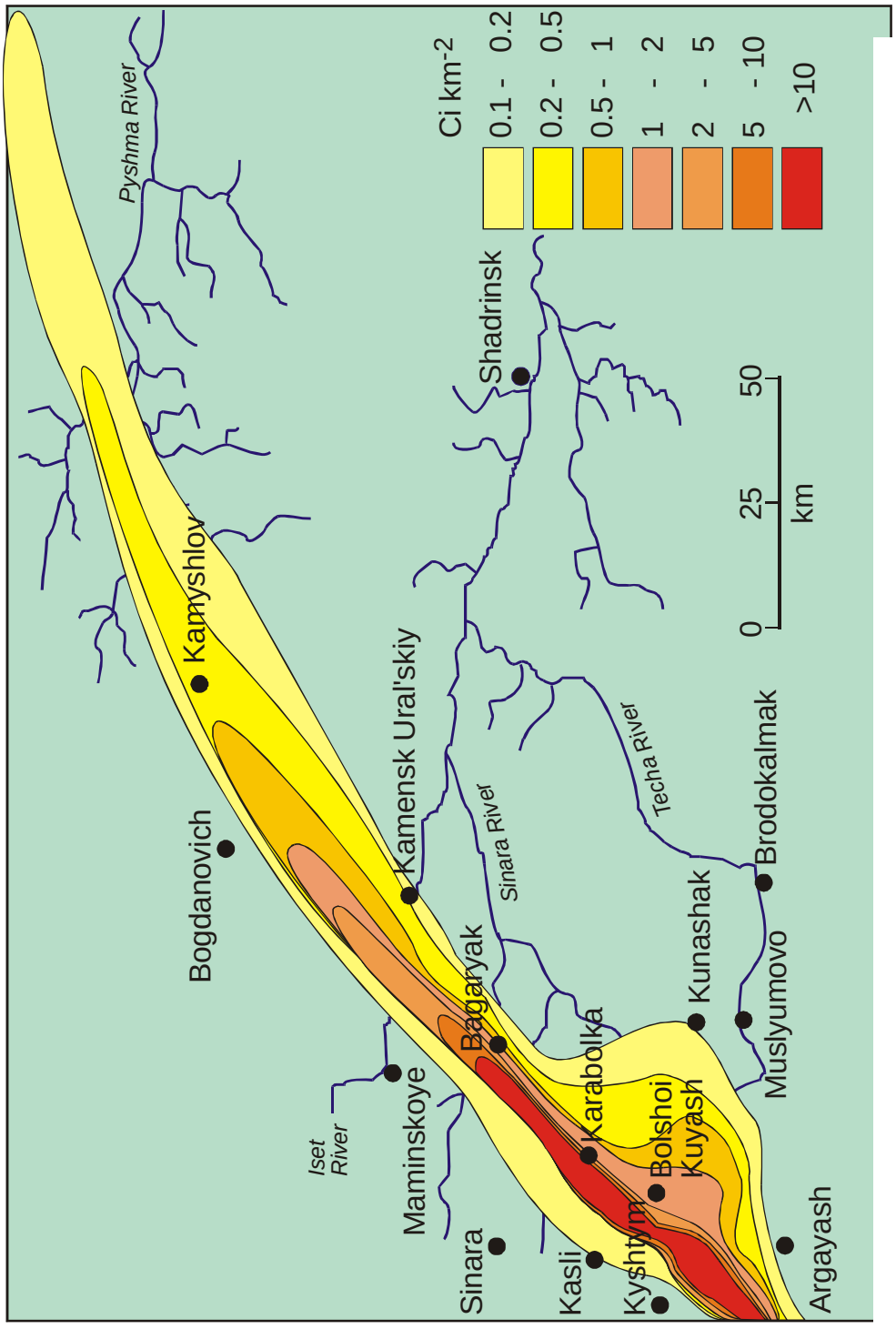


FIGURE 4 Deposition of ^{90}Sr resulting from the Kyshtym accident
(1 Bq ≅ 2.7 10^{-11} Ci)

4.1.5 International Nuclear Event Scale ranking

The Kyshtym accident would probably have been ranked at Level 6, a serious accident, because of the external release of fission products and the widespread removal of people.

4.2 Windscale

4.2.1 Facility (Atomic Energy Office, 1957)

The Windscale plant was located on the Cumbrian coast of north-west England. This plant was operated by the United Kingdom Atomic Energy Authority, where two identical graphite moderated natural uranium reactors were used for plutonium production. The reactors were cooled by drawing air through each reactor by large fans. This air was subsequently filtered and discharged through a high chimney. Wigner energy, stored in the graphite lattice of the reactor, was periodically released by an annealing process.

4.2.2 Nature of the accident (Crick, M J and Linsley, G S, 1982; Simmonds, J R, *et al*, 1995)

On 7 October 1957, during a routine shut-down of the No. 1 reactor, nuclear heating was used to initiate the Wigner release. An instrumentation error coupled with inadequate reporting of reactor temperatures caused the fuel to start to melt. Initial attempts to cool the reactor failed and a fire resulted, involving uranium metal fuel and graphite. The first release of radioactivity was detected on 10 October 1957. Following various unsuccessful measures, water was injected to cool the reactor core.

4.2.3 Radionuclides released (Crick, M J and Linsley, G S, 1982; Simmonds, J R, *et al*, 1995)

The once-through air cooling system allowed fission products to be released to the chimney. Filters significantly reduced the quantities of radioactive fission fragments released but were not effective in preventing the release of volatile elements such as iodine and noble gases. Polonium-210, which was being produced in the reactor, was also released. Estimates of the radionuclides released during the Windscale fire are shown in Table 8. The deposition of ^{131}I resulting from the accident is illustrated in Figure 5(a) (Crick, M J and Linsley, G S, 1982; Simmonds, J R, *et al*, 1995) and the resulting concentration in milk on 13 October 1957 is illustrated in Figure 5(b) (Loutit, J F, *et al*, 1960).

TABLE 8 Radionuclides released during the Windscale fire (Crick, M J and Linsley, G S, 1982; Simmonds, J R, *et al*, 1995)

Radionuclide	Activity released (TBq)
^{3}H	5,000
^{85}Kr	59
^{89}Sr	3
^{90}Sr	0.074
^{106}Ru	3
^{129}Te	31
^{129m}Te	31
^{131}I	740
^{132}Te	440
^{133}Xe	16,000
^{135}Xe	44
^{137}Cs	22
^{144}Ce	3
^{210}Po	8.8
^{239}Pu	0.0016

4.2.4 Radiation doses and countermeasures (Crick, M J and Linsley, G S, 1982; Simmonds, J R, *et al*, 1995; Clarke, R H, 1989)

The exposure pathway of principal concern was consumption of ^{131}I in cows' milk. Milk bans were implemented which reduced the intake of radioiodine. Thyroid doses in the local population were estimated to be up to 20 mSv for adults and up to 60 mSv for children. However, the maximum measured activity in a child's thyroid was reported to correspond to a thyroid dose equivalent of about 160 mSv. By including exposure to other radionuclides and pathways, a maximum individual effective dose of about 9 mSv has been estimated. Table 9 shows the collective effective dose received by the population in Cumbria, the UK, and Europe as a result of the accident.

TABLE 9 Collective effective dose (manSv) due to the Windscale fire (Crick, M J and Linsley, G S, 1985; Simmonds, J R, *et al*, 1995; Clarke, R H, 1989)

Pathway	Cumbria	UK	Europe
Inhalation	35	900	980
Ingestion of milk	88	570	590
Other foods	12	170	190
External from plume	4.9	54	57
External from ground deposition	12	190	210
Total (rounded)	150	1,900	2,000

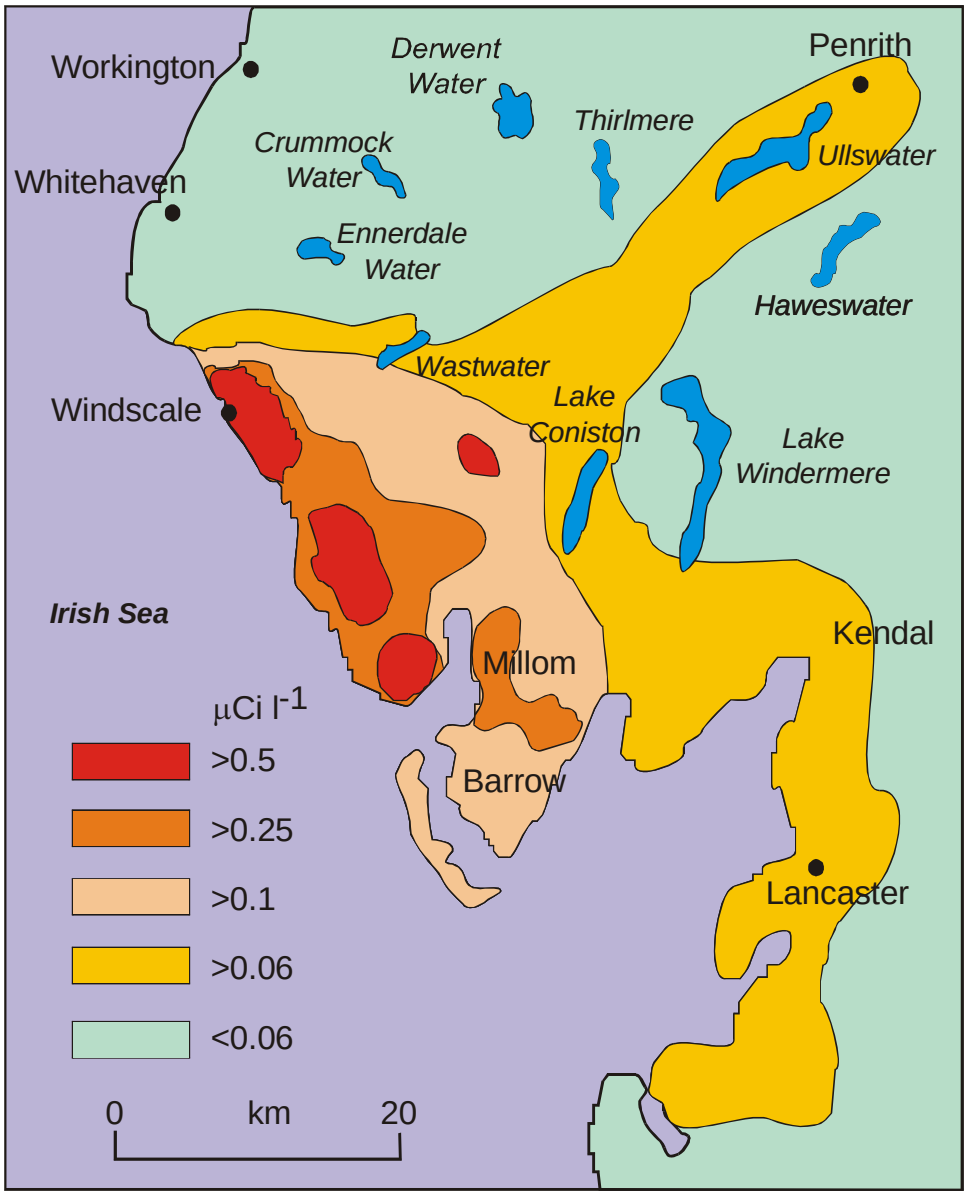


FIGURE 5(a) Deposition of ^{131}I in northern England following the Windscale fire (Crick, M J and Linsley, G S, 1982; Simmonds, J R, *et al*, 1995)

4.2.5 International Nuclear Event Scale ranking

The Windscale accident would have been ranked at Level 5, an accident with off-site risks, due to the external release of fission products.

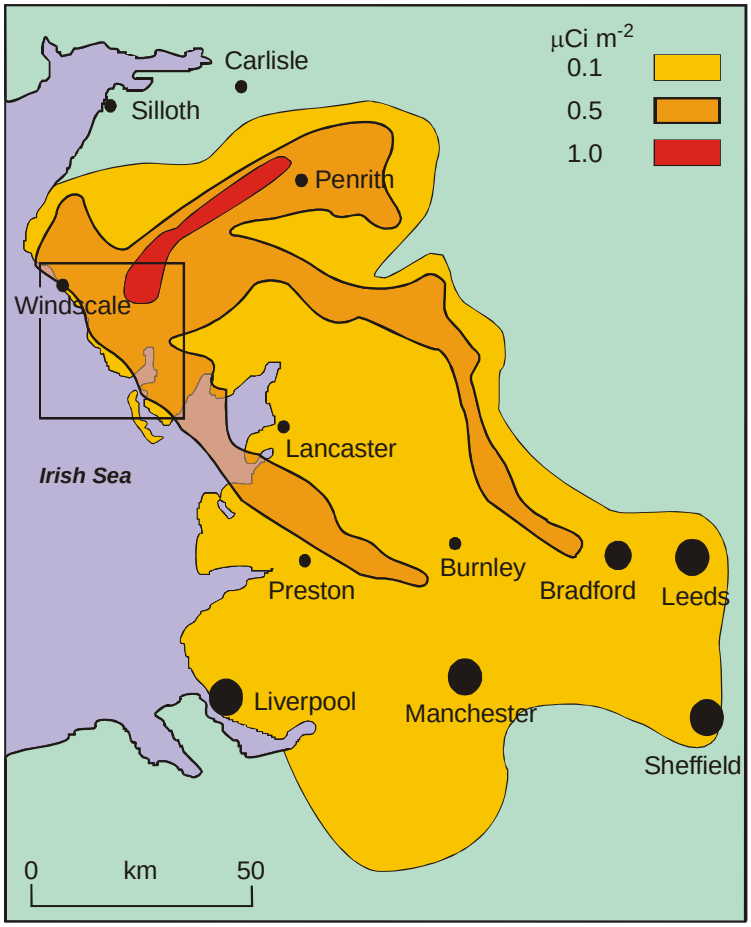


FIGURE 5(b) Radioiodine contamination in milk on 13 October 1957 following the Windscale fire (Loutit, J F, *et al*, 1960)

4.3 Palomares

4.3.1 Nature of the accident (Mettler, F A, *et al*, 1990)

On 17 January 1966, a collision occurred between an American B-52 bomber and a service aircraft during a mid-air refuelling operation. The collision occurred over the village of Palomares in the Almeria region of Spain. The B-52 was carrying four thermonuclear bombs, two of which were recovered intact following the accident. The other two bombs suffered a failure of their parachute systems. On impact with the ground their conventional high explosives detonated and part of the core contents ignited releasing an aerosol of radioactive material.

4.3.2 Radionuclides released (Mettler, F A, *et al*, 1990)

The only radionuclide released that was of radiological significance was plutonium-239. An area of approximately 2.6 km^2 was contaminated.

4.3.3 Radiation doses and countermeasures (Mettler, F A, *et al*, 1990; Espinosa, A, *et al*, 1998)

The radiation doses received shortly after the accident would have arisen from inhalation of airborne plutonium. Whole body monitoring of members of the local population who were most likely to have received an intake was carried out.

Recent dose assessments suggest that members of the public did not receive doses in excess of 1 mSv y^{-1} as a result of the accident.

The principal countermeasure implemented was the decontamination of agricultural land. The surface cover of the most highly contaminated areas, some 0.02 km^2, was removed and over 1,000 m^3 of waste was packaged and dispatched to the USA for storage and ultimate disposal.

4.4 COSMOS 954

4.4.1 Facility details (Gummer, W K, *et al*, 1980)

In September 1977, the USSR launched the COSMOS 954 satellite which was powered by a small nuclear reactor and weighed several tonnes. From an early point in its operation the satellite proved problematical and its early return to Earth was considered likely but difficult to forecast. The satellite, and its reactor in particular, were designed to burn up on re-entry to the Earth's atmosphere.

4.4.2 Nature of the accident (Gummer, W K, *et al*, 1980)

In mid-January 1978, the American government, which had been tracking the satellite, warned other potentially affected countries of its imminent descent. The satellite's descent on 24 January 1978 was tracked over Canada and observed by a few people in the sparsely populated North Western Territories. An operation was put into place to search for and recover the debris. This involved Canadian and American agencies and extended over an area in excess of 100,000 km^2.

4.4.3 Radionuclides released (Gummer, W K, *et al*, 1980)

Numerous large items were found, some of them intensely radioactive with dose rates at 1 m in excess of 1 mGy h^{-1}. Over 4,000 very small radioactive particles were subsequently found. It was estimated that approximately 20% of the satellite's nuclear fuel descended to earth. The total deposited activity was estimated to be nearly 100 TBq. The material recovered amounted to an estimated 0.1% of the satellite's inventory of radionuclides. Radiologically the most significant radionuclides were ^{95}Zr, ^{95}Nb, ^{103}Ru and ^{106}Ru.

4.4.4 Radiation doses and countermeasures(Gummer, W K, *et al*, 1980)

The sparse population made it difficult to make reliable estimates of the levels of exposure to members of the public. Checks on local people, who had discovered items of debris, however, showed no observable adverse effects on health.

The principal countermeasure implemented was the search for, and recovery of, radioactive debris. Doses to workers involved in the clean-up were monitored and found to be less than 5 mSv.

4.5 Three Mile Island

4.5.1 Facility (Report of the President's Commission, 1979)

The Three Mile Island nuclear power station is located in Pennsylvania in the North Eastern USA. The station consisted of two pressurised water reactors (PWR); Reactor 2 commenced operation in 1978.

4.5.2 Nature of the accident (Report of the President's Commission, 1979)

On 28 March 1979, a minor technical fault in Reactor 2 led to a complex chain of events involving the reactor cooling systems. As a consequence, the reactor lost water from its primary cooling circuit and fuel temperatures rose substantially. After a number of hours, one-third of the fuel had melted and large amounts of fission products were released into the reactor containment. Some volatile fission products, primarily noble gases but with a small quantity of iodine, escaped into an adjacent building and were released to atmosphere.

4.5.3 Radionuclides released (Gudiksen, P H and Dickerson, M H, 1991)

Estimates of the releases of radionuclides to the environment are shown in Table 10. Only small quantities of radioiodine were released, compared with noble gases, because of the complex pathway from the core to atmosphere and because the intact containment system only allowed air to be released through a filtration system. In addition, since Reactor 2 had only commenced operation a year before the accident occurred, the fission product inventory was still relatively low when the accident occurred.

TABLE 10 Radionuclides released during the Three Mile Island accident (Gudiksen, P H and Dickerson, M H, 1991)

Radionuclide	Activity released (TBq)
^{88}Kr	2,300
^{131}I	0.5
^{133}I	0.1
^{133}Xe	310,000
^{133m}Xe	6,300
^{135}Xe	56,000
^{135m}Xe	5,200

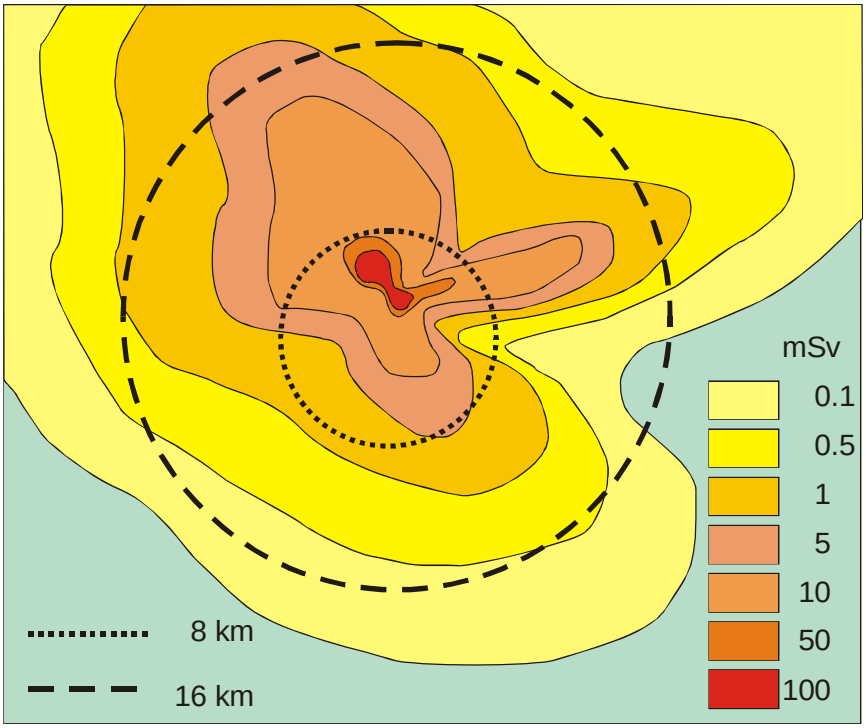
4.5.4 Radiation doses and countermeasures (Gudiksen, P H and Dickerson, M H, 1991)

The principal pathway leading to exposure of the public was external radiation from airborne noble gases. The maximum individual off-site external gamma dose was estimated to be 0.83 mSv on the basis of thermoluminescent dosemeters situated within a kilometre of the site.

The average effective dose within 1 km of the site has been estimated at 0.08 mSv and the highest individual thyroid dose at less than 0.2 mSv. The collective thyroid and effective dose equivalent commitments within 80 km were in the range 14–28 man Sv and 16–53 man Sv, respectively. The estimated distribution of doses in the area around the site is illustrated in Figure 6 (Gudiksen, P H and Dickerson, M H, 1991).

During the course of the accident, authorities advised pregnant women and pre-school children living within 5 miles (8 km) of the plant to leave and people living within 10 miles to remain indoors. The population within 5 miles of the plant was reported to number approximately 25,000.

FIGURE 6 Three Mile Island: estimated distribution of doses



Since the release consisted almost entirely of noble gases, there was virtually no ground deposition and consequently no requirement for food restrictions or longer term countermeasures.

4.5.5 International Nuclear Event Scale ranking

The Three Mile Island accident would have been ranked at Level 5 on the International Nuclear Event Scale, as an accident with off-site risks, although the determining criterion in this case was the severe damage to a large fraction of the core rather than the release of fission products to atmosphere.

4.6 Goiânia

4.6.1 Facility

Following the break up in 1985 of a medical partnership in Goiânia, Brazil, a teletherapy unit containing a highly radioactive source was abandoned on the partly demolished premises. The source, 50.9 TBq of ^{137}Cs, was in the form of a highly soluble caesium chloride salt, compacted and doubly sealed inside stainless steel.

4.6.2 Nature of the accident (International Atomic Energy Agency, 1988)

In September 1987, local people searching for scrap metal removed the source from its housing in the teletherapy machine. In doing so they unwittingly ruptured the source and subsequently spread contamination widely across the city. The grains of caesium salt emitted a blue glow making it highly desirable. Although the nature of this glow was not fully understood at the time, it has subsequently been thought to be associated with fluorescence or Cerenkov radiation.

Several local people, who had by now suffered serious radiation exposure, began to exhibit illness. One person, whose family was affected, presented a piece of the source to a doctor suggesting it was responsible for the illness. After various explanations were considered, radiation was suspected as the cause and assistance was sought from a visiting medical physicist who confirmed very high radiation readings.

4.6.3 Radiation doses and countermeasures (International Atomic Energy Agency, 1988)

Twenty-one people were estimated to have received doses in excess of 1 Gy, the highest of which was approximately 7 Gy. Four people died and many more suffered radiation burns. A few individuals received intakes of ^{137}Cs which exceeded 1 GBq.

The principal countermeasure, other than medical care for those exposed, was decontamination. This was achieved over a total period of six months and involved the demolition of seven residences and the generation of 3,500 m^3 of radioactive waste.

4.7 Chernobyl

4.7.1 Facility (Gittus, J H, *et al*, 1988)

The Chernobyl nuclear power station is situated approximately 100 km north of Kiev, in the Ukraine, close to the town of Pripyat. In 1986, four RBMK reactors were operational on the site and two more were under construction. The RBMK reactor is graphite-moderated and water cooled.

4.7.2 Nature of the accident (Gittus, J H, *et al*, 1988)

On 26 April 1986 tests were being made of electricity generation during turbine run down. The test took one of the reactors into an operating condition that was known to be unstable and could only be performed after safety systems had been bypassed. Increasing reactor instability coupled with almost total withdrawal of the control rods generated an uncontrollable rise in reactor power to approximately 100 times the normal maximum. Subsequent violent chemical reactions and heat generation caused an explosion which partially removed the concrete reactor lid, exposing the burning core and releasing radionuclides to the atmosphere. This release continued for at least ten days.

4.7.3 Radionuclides released (Organisation for Economic Corporation and Development Nuclear Energy Agency, 1995)

The radionuclides estimated to have been released are shown in Table 11. The whole core inventory of noble gases (isotopes of krypton and xenon) was released, as was about 50%–60% of the iodine in the core, 20%–40% of the caesium and approximately 3.5% of the rare earths and actinides. The deposition of ^{137}Cs in the region resulting from the Chernobyl accident is illustrated in Figure 7 (Skryabin, A M, *et al*, 1995).

TABLE 11 Radionuclides released during the Chernobyl accident (Gittus, J H, *et al*, 1988)

Radionuclide	Activity released (TBq)
^{89}Sr	115,000
^{90}Sr	10,000
^{99}Mo	>168,000
^{95}Zr	196,000
^{103}Ru	>168,000
^{106}Ru	>73,000
^{131}I	~1,760,000
^{132}Te	~1,150,000
^{137}Cs	~85,000
^{140}Ba	~240,000
^{141}Ce	196,000
^{144}Ce	~116,000
^{239}Np	~95,000
^{238}Pu	35
^{239}Pu	30
^{240}Pu	42
^{241}Pu	~6,000
^{242}Cm	~900

4.7.4 Radiation doses and countermeasures (International Atomic Energy Agency, 1991; UNSCEAR, 2000)

The extent and complexity of the radiological impact of the accident are not easy to summarise. An estimated 237 on-site workers developed acute radiation syndrome of varying severity. The resulting doses, up to 16 Gy, were principally from external beta and gamma radiation. Some individuals suffered very severe skin burns caused by contamination of skin and clothes. No member of the public was diagnosed as exhibiting acute radiation syndrome, however.

Doses to members of the public in the affected region of the former Soviet Union have been estimated and exhibit wide distributions. Whole body doses in the first few years after the accident range up to several hundred millisieverts. Thyroid doses to those who were young children at the time of the release have been estimated to range from negligible values up to at least 40 Sv in extreme cases, which have resulted in more than 1000 cases of thyroid cancer to date (UNSCEAR, 2000).

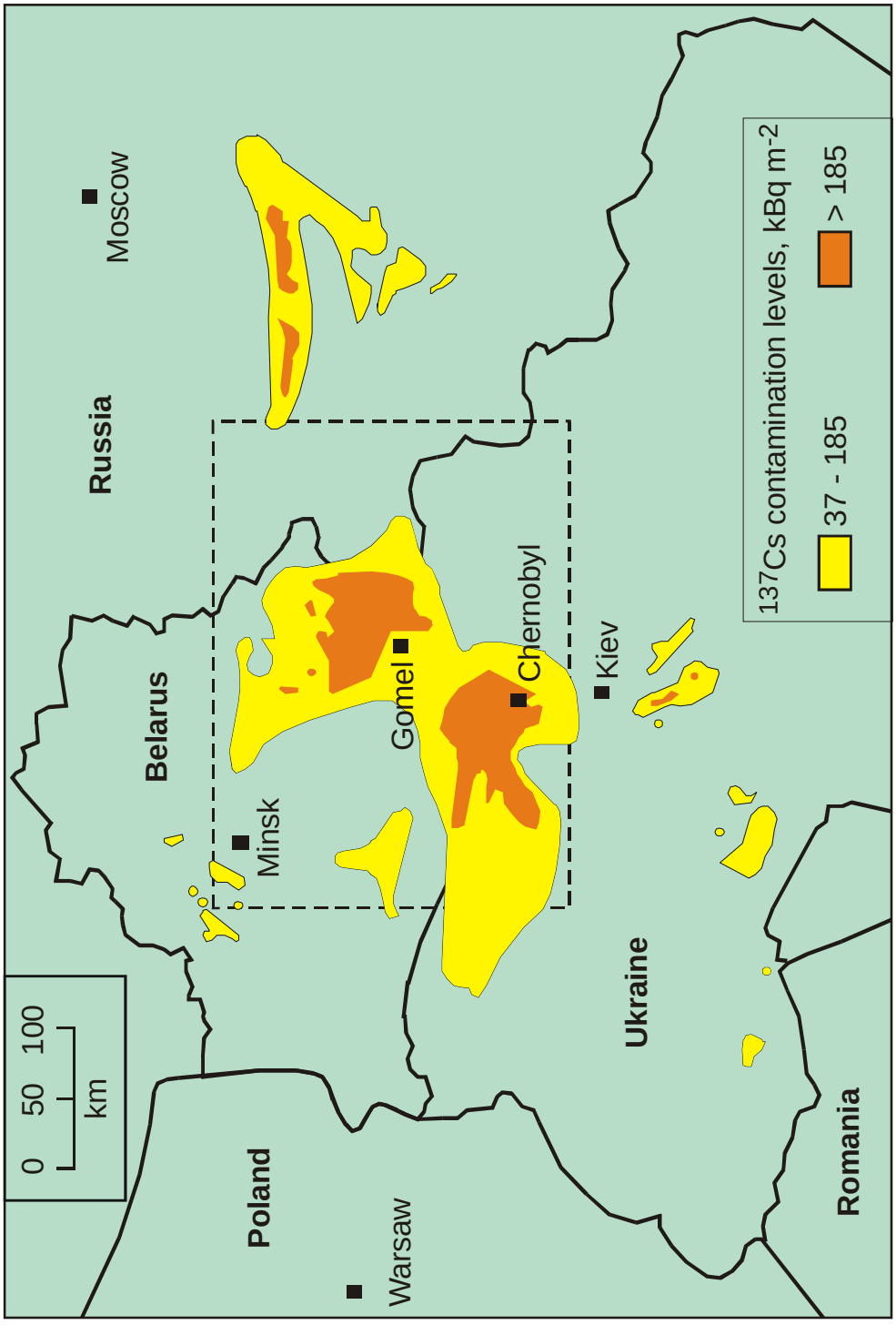


FIGURE 7 Deposition of ^{137}Cs following the Chernobyl accident

The estimated collective effective dose to the European Soviet population was in the range of 10^5 to 10^6 man Sv. The collective effective dose to the European population was approximately 8 10^5 man Sv, of which around 4% was delivered to the UK population.

Approximately 135,000 members of the public were evacuated. An exclusion zone was set up at a radius of 30 km around the site. Across significant parts of northern Europe, foodstuffs, livestock and water bodies were contaminated, resulting in extensive restrictions on sale and consumption of some foods. Restrictions within the affected areas of the former Soviet Union and other countries are expected to remain in place for a number of years.

UNSCEAR (UNSCEAR, 2000) has estimated average doses to those persons who were evacuated following the accident to be 30 mSv. For persons continuing to reside in contaminated areas the dose has been estimated to be 10 mSv in the first decade following the accident. UNSCEAR notes that maximum values of dose may be an order of magnitude higher.

There have been about 1,800 cases, to date, of thyroid cancer in children who were exposed at the time of the accident. No other adverse health effect in the population have been observed as yet.

4.7.5 International Nuclear Event Scale ranking

The Chernobyl accident ranks at Level 7 on the International Nuclear Event Scale, as a major accident with off-site risks, because of the external release with widespread environmental and human health effects.

4.8 Other incidents

Other nuclear and radiological accidents have occurred that have involved serious radiation exposure of workers or the accidental release of radionuclides to the environment (International Atomic Energy Agency, 1976; Hubner, K F and Fry, S A, 1980; Ricks, R C and Fry, S A, 1990; De Olivier, A R, 1987).

5 RADIOLOGICAL ASSESSMENT

5.1 Introduction

This section presents models and data which may be used to carry out emergency response calculations. The information may also be useful when developing emergency plans, although its use in this context should be carefully considered to ensure that it is appropriate.

An overview is presented of the environmental transfer processes that may be important when radionuclides are accidentally released to atmosphere. The important pathways of exposure are described and methods are provided for

assessing them, using the accompanying technical data. Accidents do arise which do not involve a release to atmosphere. Other routes of exposure are therefore possible, including direct source exposure and release of radionuclides to water bodies. These accident types are not considered further here.

Technical data are presented for a range of radionuclides which are most likely to be of radiological significance in the event of an accident. Information on the decay properties and principal radiation emissions of these radionuclides are shown in Table 12. These data were taken from the JEF2 (Organisation for Economic Cooperation and Development Nuclear Energy Agency, 1994) compilation.

5.2 Source term

The source term for a nuclear accident may be defined as the quantity, rate of release, and physical and chemical characteristics of the radionuclides released, together with the position and height at which the release takes place and the heat content of the released plume. Each of these has an influence on the radiological impact of a release and a knowledge of any or all of these factors may assist in making decisions associated with protection measures and radiation monitoring activities.

The very nature of an accidental and potentially uncontrolled release of radionuclides results in a lack of detailed source term information being available at an early stage. Thus, in practice, measurements of environmental contamination usually provide the most immediate means of determining the off-site impact of the release. If a source term estimate is available it may be used with the various models described here to gauge the likely consequent environmental distribution of radionuclides and associated radiation exposures. Estimates of the source term may be made by a number of means including assessment of on-site conditions and the interpretation of levels of environmental contamination and atmospheric dispersion and deposition conditions. Assessments based on engineering judgement and plant conditions are outside the scope of this report. Source term estimation, based on observed airborne radionuclide concentrations, is discussed briefly in Section 6.

5.3 Environmental transfer following release to atmosphere

A number of processes play important roles in determining the radiological impact of an accidental release of radionuclides to atmosphere. Knowledge of relevant parameters coupled with appropriate models may allow reasonable estimates to be made of environmental concentrations of radionuclides and their resulting radiological significance. In emergency situations it is often the case that some of the determining factors are either not known or are subject to great uncertainty. Emergency assessments are therefore likely to be based on incomplete or uncertain information. These uncertainties limit the scope, accuracy and precision of calculations that may be made in the short term. In

the following paragraphs, the most significant transfer processes are introduced, together with their associated radiation exposure pathways.

TABLE 12 Selected radionuclide decay properties

Nuclide	Half-life	Principal gamma emissions (keV)	Principal maximum beta emissions (keV)	Principal alpha emissions (keV)
^{3}H	12.33 y	–	18.6	–
^{41}Ar	1.83 h	1293.6	1198.1	–
^{60}Co	5.27 y	1332.5, 1173.2	317.8	–
^{85}Kr	10.72 y	–	687.0	–
^{85m}Kr	4.48 h	151.2	841.0	–
^{87}Kr	1.27 h	402.6	3486.0	–
^{88}Kr	2.84 h	2392.1	520.9	–
^{89}Sr	50.50 d	–	1492.1	–
$^{90}Sr/^{90}Y$*	29.12 y	–	2283.9	–
^{95}Zr	63.98 d	756.7, 724.2	365.0	–
^{95}Nb	35.15 d	765.8	159.7	–
^{103}Ru	39.35 d	497.1	225.0	–
$^{106}Ru/^{106}Rh$*	1.01 y	511.9	3541.0	–
^{132}Te	3.26 d	228.2	215.0	–
^{131}I	8.04 d	364.5	606.3	–
^{132}I	2.30 h	667.7, 772.6	2140.0	–
^{133}I	20.80 h	529.9	1230.1	–
^{135}I	6.61 h	1260.4, 1131.5	1450.6	–
^{133}Xe	5.25 d	81.0	346.0	–
^{135}Xe	9.09 h	249.8	908.2	–
^{134}Cs	2.06 y	604.6, 795.8	658.0	–
$^{137}Cs/^{137m}Ba$*	30.00 y	661.6	511.6	–
^{140}Ba	12.74 d	537.3	991.2	–
^{140}La	1.68 d	1596.2, 487.0	1348.2	–
$^{144}Ce/^{144}Pr$*	284.90 d	–	2996.0	–
^{234}U	$2.46\ 10^{5}$ y	–	–	4774.9
^{235}U	$7.04\ 10^{8}$ y	185.7	–	4396.0
^{238}U	$4.47\ 10^{9}$ y	–	–	4198.5
^{238}Pu	87.70 y	–	–	5499.3
^{239}Pu	$2.41\ 10^{4}$ y	–	–	5156.2
^{241}Pu	14.40 y	–	20.8	–
^{241}Am	432.71 y	59.5	–	5485.6
^{242}Cm	162.94 d	–	–	6112.9
^{244}Cm	18.10 y	–	–	5805.0

*For these radionuclides, short-lived decay products contribute significantly to gamma/beta emissions.

5.3.1 Atmospheric dispersion and deposition

Radioactive material released to atmosphere is transported and dispersed according to the prevailing meteorological conditions and, in general, will ultimately be deposited on surfaces. With sufficient knowledge of the atmospheric and radionuclide release conditions, it is possible to estimate the likely atmospheric or ground concentrations of radionuclides that might be observed downwind of a release point. These processes, and appropriate means of modelling them, are described in Section 6.

Exposure pathways arising from atmospheric dispersion and deposition processes include inhalation of airborne radionuclides, external irradiation from airborne radionuclides, irradiation of the skin from radionuclides deposited on to the skin, and external gamma irradiation from radionuclides deposited on the ground.

5.3.2 Contamination of the foodchain and water supplies

Airborne radionuclides may be deposited directly on to vegetation or transferred through the environment into foodstuffs. The dynamics of this environmental transfer depend on the physical, chemical and environmental behaviour of the radionuclides, the foodstuffs concerned, seasonal growth and agricultural practices. The primary exposure pathway is the consumption of contaminated foodstuffs.

Radionuclides may be deposited directly on to water bodies or carried as runoff into them. The processes involved are often very site specific and are not amenable to generic modelling. However, significant contamination of mains public drinking water supplies is unlikely to occur owing to the very substantial dilution, time delay and filtration processes which are part of most drinking water supply routes. There may be potential for elevated levels of contamination of non-mains water supplies obtained by methods such as rooftop collection. The most appropriate means of assessing the radiological significance of potential contamination of drinking water supplies is through a suitable sample collection and analysis programme.

5.3.3 Resuspension of deposited radionuclides

Radionuclides deposited on the ground may be resuspended into the atmosphere by natural or man-made disturbance. Radiation exposure may result from inhalation of the resuspended radionuclides.

5.4 Exposure pathways

This section describes models and data that may be used to assess exposure pathways following an accidental release of radionuclides to atmosphere.

5.4.1 Inhalation of the airborne radionuclides

For many accidental releases considered in consequence studies and emergency plans (except releases consisting mostly of noble gases) the most significant short-term exposure pathway is the inhalation of airborne radionuclides. Equation 1 provides a means of estimating the time integral of radionuclide

concentration in air at a location given a measurement, made at the same location, of the radionuclide concentration in air.

More sophisticated methods may be used to evaluate this integral if additional information is available. Additional information might include a series of air concentration measurements made over time or information about the variation of the release rate over time.

Equation 2 represents the committed (effective or thyroid) dose arising from inhalation of airborne radionuclides. Equation 3 represents the hourly committed (effective or thyroid) dose from inhaling a standing concentration of airborne contamination.

$$TIAC_n = AC_n \times RD \quad (1)$$

$$ID_{org,age} = BR_{age} \times \sum_n (TIAC_n \times IDF_{org,age,n}) \quad (2)$$

where $TIAC_n$ = time-integrated concentration of radionuclide n in air (Bq s m^{-3})

AC_n = instantaneous concentration of radionuclide n in air (Bq m^{-3})

RD = duration of the release or plume presence (s)

BR_{age} = breathing rate for the age group of interest (m^3 s^{-1})

$IDF_{org, age, n}$ = thyroid or effective dose to a particular age group arising from inhaling 1 Bq of radionuclide n (Sv Bq^{-1})

$ID_{org, age}$ = organ or effective inhalation dose (Sv)

$$IDR_{org,age} = \sum_n (AC_n \times IDRF_{org,age,n}) \quad (3)$$

where $IDRF_{org, age, n}$ = organ or effective dose to someone of a particular age group arising from inhaling air contaminated with 1 Bq m^{-3} of radionuclide n for a period of 1 hour (Sv h^{-1} per Bq m^{-3})

$IDR_{org, age}$ = hourly organ or effective inhalation dose rate (Sv h^{-1})

Breathing rates for adults, children (age ten years) and infants (age one year) are shown in Table 13 (Robinson, 1996).

TABLE 13 Breathing rates

Age group	Breathing rate	
	m^3 s^{-1}	m^3 h^{-1}
Adult	2.3 10^{-4}	0.8
Child (10 years)	1.8 10^{-4}	0.6
Infant (1 year)	6.0 10^{-5}	0.2

Effective dose conversion factors for the three age groups above are given in Table 14(a) (International Commission on Radiological Protection, 1996a).

Thyroid dose conversion factors for isotopes of radioiodine are given in Table 14(b) (International Commission on Radiological Protection, 1996b). The nuclide ^{132}Te is included in Table 14(b) because of its decay product, ^{132}I. For elements likely to be released in particulate form, inhalation dose coefficients are presented for an aerodynamic particle size of 1 μm (International Commission on Radiological Protection, 1996a). In the absence of specific information, default recommended (International Commission on Radiological Protection, 1996b) absorption types are used. For tritium, dose coefficients are presented for tritiated water in vapour form. For isotopes of iodine, inhalation dose coefficients are based on the assumption (International Commission on Radiological Protection, in press) of equal proportions of particulate activity in the default absorption type (International Commission on Radiological Protection, 1996b) (F) and elemental iodine in the vapour form (Vap) (International Commission on Radiological Protection, 1996b). Separate inhalation dose coefficients for radioiodine in particulate and vapour forms have been included. For uranium isotopes, dose coefficients are presented for the default particulate absorption type (International Commission on Radiological Protection, 1996b) (M). Dose coefficients for uranium are also presented for absorption type F. These may be applicable in situations, such as releases of uranium hexafluoride, where uranium is released in, or rapidly converted to, chemical forms associated with type F behaviour (International Commission on Radiological Protection, 1996b). Guidance (International Commission on Radiological Protection, in press) on absorption types and values of appropriate dose coefficients (International Commission on Radiological Protection, 1996a; International Commission on Radiological Protection, 1996b) are available for use in situations where more detailed information is known about the physical and chemical form of radionuclides released.

If an assessment of inhalation doses requires consideration of the effect of being indoors, possibly to evaluate the doses saved due to sheltering, an inhalation dose location factor is used to relate the estimated inhalation dose received by a person indoors to the outdoor level.

A review (Andersson, K G, *et al*, 1995) of inhalation dose location factors indicated that, for typical UK buildings, a location factor of 0.5 should be used for both 1 μm depositing particles and iodine vapour. Equations 4 and 5 may be used to estimate the committed inhalation dose and dose rate, modified by an inhalation location factor LF_{inh}, arising from a time-integrated or instantaneous concentration of radionuclides in air.

$$ID_{org,age} = LF_{inh} \times BR_{age} \times \sum_{n} (TIAC_n \times IDF_{org,age,n}) \qquad (4)$$

$$IDR_{org,age} = LF_{inh} \times \sum_{n} (AC_n \times IDRF_{org,age,n}) \qquad (5)$$

where LF_{inh} = inhalation dose location factor for the situation

TABLE 14(a) Inhalation pathway - effective dose conversion factors*

Nuclide	Absorption type	Committed dose per unit intake (Sv per Bq)			Committed dose per unit integrated air concentration (Sv per Bq s m^{-3})			Committed dose rate per unit air concentration (Sv h^{-1} per Bq m^{-3})		
		Infant	Child	Adult	Infant	Child	Adult	Infant	Child	Adult
^{3}H	V	$4.8\ 10^{-11}$	$2.3\ 10^{-11}$	$1.8\ 10^{-11}$	$2.9\ 10^{-15}$	$4.1\ 10^{-15}$	$4.1\ 10^{-15}$	$1.0\ 10^{-11}$	$1.5\ 10^{-11}$	$1.5\ 10^{-11}$
^{60}Co	M	$3.4\ 10^{-8}$	$1.5\ 10^{-8}$	$1.0\ 10^{-8}$	$2.0\ 10^{-12}$	$2.7\ 10^{-12}$	$2.3\ 10^{-12}$	$7.3\ 10^{-9}$	$9.7\ 10^{-9}$	$8.3\ 10^{-9}$
^{89}Sr	M	$2.4\ 10^{-8}$	$9.1\ 10^{-9}$	$6.1\ 10^{-9}$	$1.4\ 10^{-12}$	$1.6\ 10^{-12}$	$1.4\ 10^{-12}$	$5.2\ 10^{-9}$	$5.9\ 10^{-9}$	$5.1\ 10^{-9}$
^{90}Sr	M	$1.1\ 10^{-7}$	$5.1\ 10^{-8}$	$3.6\ 10^{-8}$	$6.6\ 10^{-12}$	$9.2\ 10^{-12}$	$8.3\ 10^{-12}$	$2.4\ 10^{-8}$	$3.3\ 10^{-8}$	$3.0\ 10^{-8}$
^{95}Zr	M	$1.6\ 10^{-8}$	$6.8\ 10^{-9}$	$4.8\ 10^{-9}$	$9.6\ 10^{-13}$	$1.2\ 10^{-12}$	$1.1\ 10^{-12}$	$3.5\ 10^{-9}$	$4.4\ 10^{-9}$	$4.0\ 10^{-9}$
^{95}Nb	M	$5.2\ 10^{-9}$	$2.2\ 10^{-9}$	$1.5\ 10^{-9}$	$3.1\ 10^{-13}$	$4.0\ 10^{-13}$	$3.5\ 10^{-13}$	$1.1\ 10^{-9}$	$1.4\ 10^{-9}$	$1.2\ 10^{-9}$
^{103}Ru	M	$8.4\ 10^{-9}$	$3.5\ 10^{-9}$	$2.4\ 10^{-9}$	$5.0\ 10^{-13}$	$6.3\ 10^{-13}$	$5.5\ 10^{-13}$	$1.8\ 10^{-9}$	$2.3\ 10^{-9}$	$2.0\ 10^{-9}$
^{106}Ru	M	$1.1\ 10^{-7}$	$4.1\ 10^{-8}$	$2.8\ 10^{-8}$	$6.6\ 10^{-12}$	$7.4\ 10^{-12}$	$6.4\ 10^{-12}$	$2.4\ 10^{-8}$	$2.7\ 10^{-8}$	$2.3\ 10^{-8}$
^{132}Te	M	$1.3\ 10^{-8}$	$4.0\ 10^{-9}$	$2.0\ 10^{-9}$	$7.8\ 10^{-13}$	$7.2\ 10^{-13}$	$4.6\ 10^{-13}$	$2.8\ 10^{-9}$	$2.6\ 10^{-9}$	$1.7\ 10^{-9}$
^{131}I	F/Vap	$1.2\ 10^{-7}$	$3.4\ 10^{-8}$	$1.4\ 10^{-8}$	$7.2\ 10^{-12}$	$6.1\ 10^{-12}$	$3.2\ 10^{-12}$	$2.6\ 10^{-8}$	$2.2\ 10^{-8}$	$1.2\ 10^{-8}$
	F	$7.2\ 10^{-8}$	$1.9\ 10^{-8}$	$7.4\ 10^{-9}$	$4.3\ 10^{-12}$	$3.4\ 10^{-12}$	$1.7\ 10^{-12}$	$1.6\ 10^{-8}$	$1.2\ 10^{-8}$	$6.1\ 10^{-9}$
	Vap	$1.6\ 10^{-7}$	$4.8\ 10^{-8}$	$2.0\ 10^{-8}$	$9.6\ 10^{-12}$	$8.6\ 10^{-12}$	$4.6\ 10^{-12}$	$3.5\ 10^{-8}$	$3.1\ 10^{-8}$	$1.7\ 10^{-8}$
^{132}I	F/Vap	$1.6\ 10^{-9}$	$4.3\ 10^{-10}$	$2.0\ 10^{-10}$	$9.6\ 10^{-14}$	$7.7\ 10^{-14}$	$4.6\ 10^{-14}$	$3.5\ 10^{-10}$	$2.8\ 10^{-10}$	$1.7\ 10^{-10}$
	F	$9.6\ 10^{-10}$	$2.2\ 10^{-10}$	$9.4\ 10^{-11}$	$5.8\ 10^{-14}$	$4.0\ 10^{-14}$	$2.2\ 10^{-14}$	$2.1\ 10^{-10}$	$1.4\ 10^{-10}$	$7.8\ 10^{-11}$
	Vap	$2.3\ 10^{-9}$	$6.4\ 10^{-10}$	$3.1\ 10^{-10}$	$1.4\ 10^{-13}$	$1.2\ 10^{-13}$	$7.1\ 10^{-14}$	$5.0\ 10^{-10}$	$4.1\ 10^{-10}$	$2.6\ 10^{-10}$
^{133}I	F/Vap	$3.0\ 10^{-8}$	$6.8\ 10^{-9}$	$2.8\ 10^{-9}$	$1.8\ 10^{-12}$	$1.2\ 10^{-12}$	$6.4\ 10^{-13}$	$6.5\ 10^{-9}$	$4.4\ 10^{-9}$	$2.3\ 10^{-9}$
	F	$1.8\ 10^{-8}$	$3.8\ 10^{-9}$	$1.5\ 10^{-9}$	$1.1\ 10^{-12}$	$6.8\ 10^{-13}$	$3.5\ 10^{-13}$	$3.9\ 10^{-9}$	$2.5\ 10^{-9}$	$1.2\ 10^{-9}$
	Vap	$4.1\ 10^{-8}$	$9.7\ 10^{-9}$	$4.0\ 10^{-9}$	$2.5\ 10^{-12}$	$1.7\ 10^{-12}$	$9.2\ 10^{-13}$	$8.9\ 10^{-9}$	$6.3\ 10^{-9}$	$3.3\ 10^{-9}$
^{135}I	F/Vap	$6.1\ 10^{-9}$	$1.4\ 10^{-9}$	$6.2\ 10^{-10}$	$3.7\ 10^{-13}$	$2.5\ 10^{-13}$	$1.4\ 10^{-13}$	$1.3\ 10^{-9}$	$9.1\ 10^{-10}$	$5.1\ 10^{-10}$
	F	$3.7\ 10^{-9}$	$7.9\ 10^{-10}$	$3.2\ 10^{-10}$	$2.2\ 10^{-13}$	$1.4\ 10^{-13}$	$7.4\ 10^{-14}$	$8.0\ 10^{-10}$	$5.1\ 10^{-10}$	$2.6\ 10^{-10}$
	Vap	$8.5\ 10^{-9}$	$2.1\ 10^{-9}$	$9.2\ 10^{-10}$	$5.1\ 10^{-13}$	$3.8\ 10^{-13}$	$2.1\ 10^{-13}$	$1.8\ 10^{-9}$	$1.4\ 10^{-9}$	$7.6\ 10^{-10}$
^{134}Cs	F	$7.3\ 10^{-9}$	$5.3\ 10^{-9}$	$6.6\ 10^{-9}$	$4.4\ 10^{-13}$	$9.5\ 10^{-13}$	$1.5\ 10^{-12}$	$1.6\ 10^{-9}$	$3.4\ 10^{-9}$	$5.5\ 10^{-9}$
^{137}Cs	F	$5.4\ 10^{-9}$	$3.7\ 10^{-9}$	$4.6\ 10^{-9}$	$3.2\ 10^{-13}$	$6.7\ 10^{-13}$	$1.1\ 10^{-12}$	$1.2\ 10^{-9}$	$2.4\ 10^{-9}$	$3.8\ 10^{-9}$
^{140}Ba	M	$2.0\ 10^{-8}$	$7.6\ 10^{-9}$	$5.1\ 10^{-9}$	$1.2\ 10^{-12}$	$1.4\ 10^{-12}$	$1.2\ 10^{-12}$	$4.3\ 10^{-9}$	$4.9\ 10^{-9}$	$4.2\ 10^{-9}$
^{140}La	M	$6.3\ 10^{-9}$	$2.0\ 10^{-9}$	$1.1\ 10^{-9}$	$3.8\ 10^{-13}$	$3.6\ 10^{-13}$	$2.5\ 10^{-13}$	$1.4\ 10^{-9}$	$1.3\ 10^{-9}$	$9.1\ 10^{-10}$
^{144}Ce	M	$1.6\ 10^{-7}$	$5.5\ 10^{-8}$	$3.6\ 10^{-8}$	$9.6\ 10^{-12}$	$9.9\ 10^{-12}$	$8.3\ 10^{-12}$	$3.5\ 10^{-8}$	$3.6\ 10^{-8}$	$3.0\ 10^{-8}$
^{234}U	F	$1.4\ 10^{-6}$	$8.0\ 10^{-7}$	$5.6\ 10^{-7}$	$8.4\ 10^{-11}$	$1.4\ 10^{-10}$	$1.3\ 10^{-10}$	$3.0\ 10^{-7}$	$5.2\ 10^{-7}$	$4.6\ 10^{-7}$
^{234}U	M	$1.1\ 10^{-5}$	$4.8\ 10^{-6}$	$3.5\ 10^{-6}$	$6.6\ 10^{-10}$	$8.6\ 10^{-10}$	$8.1\ 10^{-10}$	$2.4\ 10^{-6}$	$3.1\ 10^{-6}$	$2.9\ 10^{-6}$
^{235}U	F	$1.3\ 10^{-6}$	$7.5\ 10^{-7}$	$5.2\ 10^{-7}$	$7.8\ 10^{-11}$	$1.4\ 10^{-10}$	$1.2\ 10^{-10}$	$2.8\ 10^{-7}$	$4.9\ 10^{-7}$	$4.3\ 10^{-7}$
^{235}U	M	$1.0\ 10^{-5}$	$4.3\ 10^{-6}$	$3.1\ 10^{-6}$	$6.0\ 10^{-10}$	$7.7\ 10^{-10}$	$7.1\ 10^{-10}$	$2.2\ 10^{-6}$	$2.8\ 10^{-6}$	$2.6\ 10^{-6}$
^{238}U	F	$1.3\ 10^{-6}$	$7.3\ 10^{-7}$	$5.0\ 10^{-7}$	$7.8\ 10^{-11}$	$1.3\ 10^{-10}$	$1.2\ 10^{-10}$	$2.8\ 10^{-7}$	$4.7\ 10^{-7}$	$4.1\ 10^{-7}$
^{238}U	M	$9.4\ 10^{-6}$	$4.0\ 10^{-6}$	$2.9\ 10^{-6}$	$5.6\ 10^{-10}$	$7.2\ 10^{-10}$	$6.7\ 10^{-10}$	$2.0\ 10^{-6}$	$2.6\ 10^{-6}$	$2.4\ 10^{-6}$
^{238}Pu	M	$7.4\ 10^{-5}$	$4.4\ 10^{-5}$	$4.6\ 10^{-5}$	$4.4\ 10^{-9}$	$7.9\ 10^{-9}$	$1.1\ 10^{-8}$	$1.6\ 10^{-5}$	$2.9\ 10^{-5}$	$3.8\ 10^{-5}$
^{239}Pu	M	$7.7\ 10^{-5}$	$4.8\ 10^{-5}$	$5.0\ 10^{-5}$	$4.6\ 10^{-9}$	$8.6\ 10^{-9}$	$1.2\ 10^{-8}$	$1.7\ 10^{-5}$	$3.1\ 10^{-5}$	$4.1\ 10^{-5}$
^{241}Pu	M	$9.7\ 10^{-7}$	$8.3\ 10^{-7}$	$9.0\ 10^{-7}$	$5.8\ 10^{-11}$	$1.5\ 10^{-10}$	$2.1\ 10^{-10}$	$2.1\ 10^{-7}$	$5.4\ 10^{-7}$	$7.5\ 10^{-7}$
^{241}Am	M	$6.9\ 10^{-5}$	$4.0\ 10^{-5}$	$4.2\ 10^{-5}$	$4.1\ 10^{-9}$	$7.2\ 10^{-9}$	$9.7\ 10^{-9}$	$1.5\ 10^{-5}$	$2.6\ 10^{-5}$	$3.5\ 10^{-5}$
^{242}Cm	M	$1.8\ 10^{-5}$	$7.3\ 10^{-6}$	$5.2\ 10^{-6}$	$1.1\ 10^{-9}$	$1.3\ 10^{-9}$	$1.2\ 10^{-9}$	$3.9\ 10^{-6}$	$4.7\ 10^{-6}$	$4.3\ 10^{-6}$
^{244}Cm	M	$5.7\ 10^{-5}$	$2.7\ 10^{-5}$	$2.7\ 10^{-5}$	$3.4\ 10^{-9}$	$4.9\ 10^{-9}$	$6.2\ 10^{-9}$	$1.2\ 10^{-5}$	$1.7\ 10^{-5}$	$2.2\ 10^{-5}$

* See main text for discussion of dosimetric parameters.

TABLE 14(b) Inhalation pathway - thyroid dose conversion factors*

Nuclide	Absorption type	Committed dose per unit intake (Sv per Bq)			Committed dose per unit integrated air concentration (Sv per Bq s m^{-3})			Committed dose rate per unit air concentration (Sv h^{-1} per Bq m^{-3})		
		Infant	Child	Adult	Infant	Child	Adult	Infant	Child	Adult
^{132}Te	M	$5.3\ 10^{-8}$	$1.1\ 10^{-8}$	$4.3\ 10^{-9}$	$3.2\ 10^{-12}$	$2.0\ 10^{-12}$	$9.9\ 10^{-13}$	$1.1\ 10^{-8}$	$7.1\ 10^{-9}$	$3.6\ 10^{-9}$
^{131}I	F/Vap	$2.3\ 10^{-6}$	$6.6\ 10^{-7}$	$2.7\ 10^{-7}$	$1.4\ 10^{-10}$	$1.2\ 10^{-10}$	$6.2\ 10^{-11}$	$5.0\ 10^{-7}$	$4.3\ 10^{-7}$	$2.2\ 10^{-7}$
	F	$1.4\ 10^{-6}$	$3.7\ 10^{-7}$	$1.5\ 10^{-7}$	$8.4\ 10^{-11}$	$6.7\ 10^{-11}$	$3.5\ 10^{-11}$	$3.0\ 10^{-7}$	$2.4\ 10^{-7}$	$1.2\ 10^{-7}$
	Vap	$3.2\ 10^{-6}$	$9.5\ 10^{-7}$	$3.9\ 10^{-7}$	$1.9\ 10^{-10}$	$1.7\ 10^{-10}$	$9.0\ 10^{-11}$	$6.9\ 10^{-7}$	$6.2\ 10^{-7}$	$3.2\ 10^{-7}$
^{132}I	F/Vap	$2.7\ 10^{-8}$	$6.2\ 10^{-9}$	$2.5\ 10^{-9}$	$1.6\ 10^{-12}$	$1.1\ 10^{-12}$	$5.8\ 10^{-13}$	$5.8\ 10^{-9}$	$4.0\ 10^{-9}$	$2.1\ 10^{-9}$
	F	$1.6\ 10^{-8}$	$3.4\ 10^{-9}$	$1.4\ 10^{-9}$	$9.6\ 10^{-13}$	$6.1\ 10^{-13}$	$3.2\ 10^{-13}$	$3.5\ 10^{-9}$	$2.2\ 10^{-9}$	$1.2\ 10^{-9}$
	Vap	$3.8\ 10^{-8}$	$8.9\ 10^{-9}$	$3.6\ 10^{-9}$	$2.3\ 10^{-12}$	$1.6\ 10^{-12}$	$8.3\ 10^{-13}$	$8.2\ 10^{-9}$	$5.8\ 10^{-9}$	$3.0\ 10^{-9}$
^{133}I	F/Vap	$5.8\ 10^{-7}$	$1.3\ 10^{-7}$	$5.2\ 10^{-8}$	$3.5\ 10^{-11}$	$2.3\ 10^{-11}$	$1.2\ 10^{-11}$	$1.3\ 10^{-7}$	$8.4\ 10^{-8}$	$4.3\ 10^{-8}$
	F	$3.5\ 10^{-7}$	$7.4\ 10^{-8}$	$2.8\ 10^{-8}$	$2.1\ 10^{-11}$	$1.3\ 10^{-11}$	$6.4\ 10^{-12}$	$7.6\ 10^{-8}$	$4.8\ 10^{-8}$	$2.3\ 10^{-8}$
	Vap	$8.0\ 10^{-7}$	$1.9\ 10^{-7}$	$7.6\ 10^{-8}$	$4.8\ 10^{-11}$	$3.4\ 10^{-11}$	$1.7\ 10^{-11}$	$1.7\ 10^{-7}$	$1.2\ 10^{-7}$	$6.3\ 10^{-8}$
^{135}I	F/Vap	$1.2\ 10^{-7}$	$2.7\ 10^{-8}$	$1.0\ 10^{-8}$	$7.2\ 10^{-12}$	$4.9\ 10^{-12}$	$2.3\ 10^{-12}$	$2.6\ 10^{-8}$	$1.7\ 10^{-8}$	$8.3\ 10^{-9}$
	F	$7.0\ 10^{-8}$	$1.5\ 10^{-8}$	$5.7\ 10^{-9}$	$4.2\ 10^{-12}$	$2.7\ 10^{-12}$	$1.3\ 10^{-12}$	$1.5\ 10^{-8}$	$9.7\ 10^{-9}$	$4.7\ 10^{-9}$
	Vap	$1.6\ 10^{-7}$	$3.8\ 10^{-8}$	$1.5\ 10^{-8}$	$9.6\ 10^{-12}$	$6.8\ 10^{-12}$	$3.5\ 10^{-12}$	$3.5\ 10^{-8}$	$2.5\ 10^{-8}$	$1.2\ 10^{-8}$

* See main text for discussion of dosimetric parameters.

In situations where radionuclides are thought to have been inhaled but for which there is significant uncertainty in the assessed intake, *in vivo* thyroid, lung or whole body monitoring or analysis of excreta samples may offer a means of improving the estimate.

5.4.2 External exposure from airborne radionuclides

Airborne beta/gamma emitting radionuclides will externally irradiate a person in the vicinity of the plume. It may be possible to use a simple model ('semi-infinite plume') to estimate exposures from this pathway using measurements of radionuclide concentrations in air and appropriate conversion factors. This model assumes that all the air, above a flat surface, is uniformly contaminated. This can have significant uncertainties in situations where the plume cannot be adequately represented as infinite in extent. An elevated plume might lead to very low air concentrations yet significantly elevated gamma dose rates at ground level. This may be particularly relevant close to the point of release.

Equally, at locations close to the release point, the assumption of infinite uniform airborne contamination may lead to overestimates of the external gamma dose rate from airborne radionuclides made on this assumption.

In many circumstances, this pathway may be assessed using direct measurements of gamma or beta dose rate. These measurements are readily made by: installed monitoring networks, usually offering time series data; hand-held monitors, which can be deployed at desired locations; or through the use of integrating dosemeters such as thermoluminescent dosemeters which may be placed at fixed points. It is important to note that when using

environmental measurements of gamma dose rate at relatively low levels, less than say 0.5–1.0 μGy h^{-1}, account must be taken of the background dose rate at the location concerned. This is best achieved when monitoring is undertaken at locations where the background dose rate is well characterised, since background rates are generally in the range of around 0.05–0.15 μGy h^{-1} in the UK. This can, however, be temporarily increased by up to a factor of two by the washout of natural radionuclides in heavy rainfall.

For situations where a measurement of the gamma dose rate is not available and where it may be assumed that a ground-level air concentration measurement is reasonably representative of the concentration of radionuclides throughout the locality, a semi-infinite plume model, as represented in equation 6, may be used. Table 15 shows effective dose rate factors (Eckerman, K F, and Ryman, J C, 1993), $ECRF_n$. Federal Guidance Report 12 (Eckerman, K F, and Ryman, J C, 1993) presents dose factors yielding effective dose equivalent. Factors presented here are for effective dose and are derived from basic data and the methodology presented by Eckerman and Ryman (Eckerman, K F, and Ryman, J C, 1993) and were extracted from software made available on the Web by those authors (http://homer.ornl.gov/VLAB/). These factors include contributions to effective dose from gamma emissions, beta emissions and Bremsstrahlung resulting from beta decay.

$$CDR = \sum_n (AC_n \times ECRF_n) \qquad (6)$$

where AC_n = instantaneous concentration of radionuclide n in air (Bq m^{-3})

$ECRF_n$ = cloud external (effective) dose rate factor (Sv h^{-1} per Bq m^{-3})

CDR = cloud (effective) dose rate (Sv h^{-1})

If the external cloud dose over time is required, the same model may be applied to the time integral rather than the instantaneous concentration. This is shown in equation 7. Table 15 also shows effective dose factors, ECF_n.

$$CD = \sum_n (TIAC_n \times ECF_n) \qquad (7)$$

where CD = cloud (effective) dose (Sv)

$TIAC_n$ = time-integrated concentration of radionuclide n in air (Bq s m^{-3})

ECF_n = cloud external (effective) dose factor (Sv per Bq s m^{-3})

If an assessment of external doses from airborne radionuclides requires consideration of the effect of being indoors, possibly to evaluate the dose saved by sheltering, a location factor is used to relate the external cloud gamma dose that might be received by a person indoors to the assessed outdoor level. A review of location factors (Brown, J and Jones, J A, 1993) indicated that for typical UK family houses a location factor of 0.2 should be used, and for

multistorey buildings a value of 0.07 should be used. The location factor for outdoors in a rural or unspecified environment is 1.0.

TABLE 15 External exposure from airborne radionuclides

Nuclide	Effective dose per unit radionuclide concentration in air	
	ECF_n (Sv per Bq s m^{-3})	$ECRF_n$ (Sv h^{-1} per Bq m^{-3})
^{41}Ar	$6.1\ 10^{-14}$	$2.2\ 10^{-10}$
^{60}Co	$1.2\ 10^{-13}$	$4.3\ 10^{-10}$
^{85}Kr	$2.4\ 10^{-16}$	$8.6\ 10^{-13}$
^{85m}Kr	$6.9\ 10^{-15}$	$2.5\ 10^{-11}$
^{87}Kr	$4.0\ 10^{-14}$	$1.4\ 10^{-10}$
^{88}Kr	$9.7\ 10^{-14}$	$3.5\ 10^{-10}$
^{89}Sr	$4.4\ 10^{-16}$	$1.6\ 10^{-12}$
^{90}Sr*	$8.9\ 10^{-16}$	$3.2\ 10^{-12}$
^{95}Zr	$3.4\ 10^{-14}$	$1.2\ 10^{-10}$
^{95}Nb	$3.5\ 10^{-14}$	$1.3\ 10^{-10}$
^{103}Ru	$2.1\ 10^{-14}$	$7.5\ 10^{-11}$
^{106}Ru*	$1.1\ 10^{-14}$	$3.8\ 10^{-11}$
^{132}Te	$9.3\ 10^{-15}$	$3.4\ 10^{-11}$
^{131}I	$1.7\ 10^{-14}$	$6.1\ 10^{-11}$
^{132}I	$1.1\ 10^{-13}$	$3.8\ 10^{-10}$
^{133}I	$2.8\ 10^{-14}$	$9.9\ 10^{-11}$
^{135}I	$7.5\ 10^{-14}$	$2.7\ 10^{-10}$
^{133}Xe	$1.3\ 10^{-15}$	$4.8\ 10^{-12}$
^{135}Xe	$1.1\ 10^{-14}$	$4.0\ 10^{-11}$
^{134}Cs	$7.1\ 10^{-14}$	$2.5\ 10^{-10}$
^{137}Cs*	$2.7\ 10^{-14}$	$9.7\ 10^{-11}$
^{140}Ba	$8.1\ 10^{-15}$	$2.9\ 10^{-11}$
^{140}La	$1.1\ 10^{-13}$	$4.0\ 10^{-10}$
^{144}Ce*	$3.4\ 10^{-15}$	$1.2\ 10^{-11}$

* Nuclides (marked thus) have short-lived decay products that contribute significantly to the exposure pathways considered here. Parent and daughters are listed below:
^{90}Sr + ^{90}Y, ^{106}Ru + ^{106}Rh, ^{137}Cs + ^{137m}Ba, ^{144}Ce + ^{144}Pr.

A location factor may also be applied to the above equation to account for the shielding offered by surrounding buildings. A location factor of 0.7 should be used in assessments of outdoor external cloud gamma doses in an urban environment (Brown, J and Jones, J A, 1993).

Modified formulations of equations 6 and 7 including an appropriate location factor, LF_{cloud}, are shown in equations 8 and 9.

$$CDR = LF_{cloud} \times \sum_n (AC_n \times ECRF_n) \quad (8)$$

$$CD = LF_{cloud} \times \sum_n (TIAC_n \times ECF_n) \quad (9)$$

where LF_{cloud} = external cloud dose location factor for the particular situation

5.4.3 Dose from skin contamination

Airborne radionuclides, other than isotopes of noble gases, may be deposited on to and irradiate exposed skin. In general, exposure from this pathway is not likely to be significant in comparison with other pathways. Experimental evidence suggests (Jones, J A, *et al*, 1998) that radionuclide deposition on to skin, whilst showing wide variations, is typically about an order of magnitude greater than deposition on to ground. Dosimetric factors have been published (Kocher, D C and Eckerman, K F, 1987) that allow estimation of doses to skin from radionuclides deposited on to skin.

5.4.4 External gamma dose from deposited radionuclides

Radionuclides deposited on to the ground and other surfaces give rise to external gamma irradiation. This exposure pathway may be assessed by dose rate monitoring if it is known that there is no significant level of airborne radionuclides present to contribute to the measured dose rate and if the normal background dose rate in the area is known or is small compared with observed levels. If the evolution of this exposure pathway over time is to be assessed or if it is to be assessed from measurements of the ground concentration of radionuclides, a model may be used. Equations 10 and 11 represent the external gamma (effective) dose rate and dose arising from deposited radionuclides. Factors $EDRF_{n,t}$ and $EDF_{n,t}$ are presented in Table 16 (Carey et al, to be published). These include the effects of radioactive decay, ingrowth of decay products, and migration of radionuclides in soil.

$$EGDR_t = \sum_n (GD_n \times EDRF_{n,t}) \qquad (10)$$

$$EGD_t = \sum_n (GD_n \times EDF_{n,t}) \qquad (11)$$

where $EGDR_t$ = effective dose rate at time t from the deposited radionuclides (Sv h^{-1})

GD_n = initial deposit of a radionuclide n (Bq m^{-2})

$EDRF_{n,t}$ = external dose rate conversion factor at time t after unit deposition of radionuclide n (Sv h^{-1} per Bq m^{-2})

EGD_t = effective dose integrated to time t from the deposited radionuclides (Sv)

$EDF_{n,t}$ = integrated external dose conversion factor to time t after unit deposition of radionuclide n (Sv per Bq m^{-2})

If an assessment of external gamma doses from deposited radionuclides requires consideration of the effect of being indoors, possibly to evaluate the dose saved by sheltering, a location factor is used to relate the external deposited gamma dose that might be received by a person indoors to the assessed outdoor level. A review of location factors has been carried out. The results are summarised in Table 17. A location factor of one (ie no reduction) should be used in assessments of outdoor external deposited gamma doses in urban and rural environments (Brown, J and Jones, J A, 1993).

TABLE 16 Gamma dose from deposited radionuclides*

(a) External dose rate ($EDRF_{n,t}$)

Dose rate (Sv h^{-1} per Bq m^{-2})	Time										
	Zero	1 day	2 days	3 days	1 week	1 month	2 months	3 months	6 months	1 year	2 years
^{60}Co	$5.6\ 10^{-12}$	$5.6\ 10^{-12}$	$5.6\ 10^{-12}$	$5.6\ 10^{-12}$	$5.6\ 10^{-12}$	$5.5\ 10^{-12}$	$5.4\ 10^{-12}$	$5.3\ 10^{-12}$	$5.0\ 10^{-12}$	$4.4\ 10^{-12}$	$3.5\ 10^{-12}$
^{95}Zr	$1.7\ 10^{-12}$	$1.7\ 10^{-12}$	$1.7\ 10^{-12}$	$1.8\ 10^{-12}$	$1.8\ 10^{-12}$	$1.9\ 10^{-12}$	$1.7\ 10^{-12}$	$1.4\ 10^{-12}$	$6.4\ 10^{-13}$	$9.4\ 10^{-14}$	$1.7\ 10^{-15}$
^{95}Nb	$1.8\ 10^{-12}$	$1.7\ 10^{-12}$	$1.7\ 10^{-12}$	$1.7\ 10^{-12}$	1.510^{-12}	$9.7\ 10^{-13}$	$5.3\ 10^{-13}$	$2.9\ 10^{-13}$	$4.6\ 10^{-14}$	$1.2\ 10^{-15}$	$8.0\ 10^{-19}$
^{103}Ru	$1.1\ 10^{-12}$	$1.1\ 10^{-12}$	$1.1\ 10^{-12}$	$1.1\ 10^{-12}$	$9.8\ 10^{-13}$	$6.5\ 10^{-13}$	$3.8\ 10^{-13}$	$2.2\ 10^{-13}$	$4.2\ 10^{-14}$	$1.6\ 10^{-15}$	$2.3\ 10^{-18}$
^{106}Ru	$4.8\ 10^{-13}$	$4.8\ 10^{-13}$	$4.8\ 10^{-13}$	$4.8\ 10^{-13}$	$4.7\ 10^{-13}$	$4.5\ 10^{-13}$	$4.2\ 10^{-13}$	$3.9\ 10^{-13}$	$3.2\ 10^{-13}$	$2.1\ 10^{-13}$	$9.7\ 10^{-14}$
^{132}Te	$4.8\ 10^{-12}$	$4.8\ 10^{-12}$	$3.9\ 10^{-12}$	$3.1\ 10^{-12}$	$1.3\ 10^{-12}$	$9.9\ 10^{-15}$	$1.7\ 10^{-17}$	$2.8\ 10^{-20}$	$8.6\ 10^{-29}$	0	0
^{131}I	$8.9\ 10^{-13}$	$8.2\ 10^{-13}$	$7.5\ 10^{-13}$	$6.9\ 10^{-13}$	$4.9\ 10^{-13}$	$6.7\ 10^{-14}$	$5.0\ 10^{-15}$	$3.7\ 10^{-16}$	$1.4\ 10^{-19}$	$2.1\ 10^{-25}$	$9.6\ 10^{-35}$
^{132}I	$5.3\ 10^{-12}$	$3.8\ 10^{-15}$	$2.7\ 10^{-18}$	$2.0\ 10^{-21}$	$5.4\ 10^{-34}$	0	0	0	0	0	0
^{133}I	$1.4\ 10^{-12}$	$6.5\ 10^{-13}$	$3.0\ 10^{-13}$	$1.4\ 10^{-13}$	$1.1\ 10^{-14}$	$2.6\ 10^{-16}$	$4.9\ 10^{-18}$	$9.2\ 10^{-20}$	$4.6\ 10^{-25}$	$1.3\ 10^{-35}$	0
^{135}I	$3.5\ 10^{-12}$	$4.2\ 10^{-13}$	$5.3\ 10^{-14}$	$7.5\ 10^{-15}$	$4.2\ 10^{-18}$	$2.2\ 10^{-36}$	0	0	0	0	0
^{134}Cs	$3.6\ 10^{-12}$	$3.6\ 10^{-12}$	$3.6\ 10^{-12}$	$3.6\ 10^{-12}$	$3.6\ 10^{-12}$	$3.5\ 10^{-12}$	$3.4\ 10^{-12}$	$3.2\ 10^{-12}$	$2.9\ 10^{-12}$	$2.3\ 10^{-12}$	$1.5\ 10^{-12}$
^{137}Cs	$1.3\ 10^{-12}$	$1.3\ 10^{-12}$	$1.3\ 10^{-12}$	$1.3\ 10^{-12}$	$1.3\ 10^{-12}$	$1.3\ 10^{-12}$	$1.3\ 10^{-12}$	$1.3\ 10^{-12}$	$1.2\ 10^{-12}$	$1.1\ 10^{-12}$	$1.0\ 10^{-12}$
^{140}Ba	$4.2\ 10^{-13}$	$2.1\ 10^{-12}$	$3.1\ 10^{-12}$	$3.7\ 10^{-12}$	$4.0\ 10^{-12}$	$1.2\ 10^{-12}$	$2.4\ 10^{-13}$	$4.6\ 10^{-14}$	$3.0\ 10^{-16}$	$1.3\ 10^{-20}$	$2.9\ 10^{-29}$
^{140}La	$5.2\ 10^{-12}$	$3.4\ 10^{-12}$	$2.3\ 10^{-12}$	$1.5\ 10^{-12}$	$2.9\ 10^{-13}$	$2.1\ 10^{-17}$	$8.7\ 10^{-23}$	$3.6\ 10^{-28}$	0	0	0
^{144}Ce	$1.1\ 10^{-13}$	$1.1\ 10^{-13}$	$1.1\ 10^{-13}$	$1.1\ 10^{-13}$	$1.1\ 10^{-13}$	$1.0\ 10^{-13}$	$9.2\ 10^{-14}$	$8.5\ 10^{-14}$	$6.6\ 10^{-14}$	$4.0\ 10^{-14}$	$1.5\ 10^{-14}$

TABLE 16 Gamma dose from deposited radionuclides*

(b) Integrated external dose ($EDF_{n,t}$)

Dose (Sv per Bq m^{-2})	Time										
	Zero	1 day	2 days	3 days	1 week	1 month	2 months	3 months	6 months	1 year	2 years
^{60}Co	0	$1.4\ 10^{-10}$	$2.7\ 10^{-10}$	$4.1\ 10^{-10}$	$9.5\ 10^{-10}$	$4.0\ 10^{-9}$	$8.0\ 10^{-9}$	$1.2\ 10^{-8}$	$2.3\ 10^{-8}$	$4.4\ 10^{-8}$	$7.8\ 10^{-8}$
^{95}Zr	0	$4.1\ 10^{-11}$	$8.3\ 10^{-11}$	$1.3\ 10^{-10}$	$3.0\ 10^{-10}$	$1.3\ 10^{-9}$	$2.6\ 10^{-9}$	$3.8\ 10^{-9}$	$6.0\ 10^{-9}$	$7.3\ 10^{-9}$	$7.5\ 10^{-9}$
^{95}Nb	0	$4.2\ 10^{-11}$	$8.4\ 10^{-11}$	$1.2\ 10^{-10}$	$2.8\ 10^{-10}$	$9.6\ 10^{-10}$	$1.5\ 10^{-9}$	$1.8\ 10^{-9}$	$2.1\ 10^{-9}$	$2.1\ 10^{-9}$	$2.1\ 10^{-9}$
^{103}Ru	0	$2.6\ 10^{-11}$	$5.2\ 10^{-11}$	$7.8\ 10^{-11}$	$1.8\ 10^{-10}$	$6.2\ 10^{-10}$	$9.8\ 10^{-10}$	$1.2\ 10^{-9}$	$1.4\ 10^{-9}$	$1.5\ 10^{-9}$	$1.5\ 10^{-9}$
^{106}Ru	0	$1.2\ 10^{-11}$	$2.3\ 10^{-11}$	$3.4\ 10^{-11}$	$8.0\ 10^{-11}$	$3.3\ 10^{-10}$	$6.5\ 10^{-10}$	$9.4\ 10^{-10}$	$1.7\ 10^{-9}$	$2.9\ 10^{-9}$	$4.2\ 10^{-9}$
^{132}Te	0	$1.1\ 10^{-10}$	$2.1\ 10^{-10}$	$3.0\ 10^{-10}$	$5.0\ 10^{-10}$	$6.5\ 10^{-10}$	$6.5\ 10^{-10}$	$6.5\ 10^{-10}$	$6.5\ 10^{-10}$	$6.5\ 10^{-10}$	$6.5\ 10^{-10}$
^{131}I	0	$2.1\ 10^{-11}$	$3.9\ 10^{-11}$	$5.7\ 10^{-11}$	$1.1\ 10^{-10}$	$2.3\ 10^{-10}$	$2.5\ 10^{-10}$	$2.5\ 10^{-10}$	$2.5\ 10^{-10}$	$2.5\ 10^{-10}$	$2.5\ 10^{-10}$
^{132}I	0	$1.7\ 10^{-11}$	$1.7\ 10^{-11}$	$1.7\ 10^{-11}$	$1.7\ 10^{-11}$	$1.7\ 10^{-11}$	$1.7\ 10^{-11}$	$1.7\ 10^{-11}$	$1.7\ 10^{-11}$	$1.7\ 10^{-11}$	$1.7\ 10^{-11}$
^{133}I	0	$2.4\ 10^{-11}$	$3.4\ 10^{-11}$	$3.9\ 10^{-11}$	$4.4\ 10^{-11}$	$4.5\ 10^{-11}$	$4.5\ 10^{-11}$	$4.5\ 10^{-11}$	$4.5\ 10^{-11}$	$4.5\ 10^{-11}$	$4.5\ 10^{-11}$
^{135}I	0	$3.6\ 10^{-11}$	$4.0\ 10^{-11}$	$4.0\ 10^{-11}$	$4.1\ 10^{-11}$	$4.1\ 10^{-11}$	$4.1\ 10^{-11}$	$4.1\ 10^{-11}$	$4.1\ 10^{-11}$	$4.1\ 10^{-11}$	$4.1\ 10^{-11}$
^{134}Cs	0	$8.7\ 10^{-11}$	$1.7\ 10^{-10}$	$2.6\ 10^{-10}$	$6.1\ 10^{-10}$	$2.6\ 10^{-9}$	$5.0\ 10^{-9}$	$7.4\ 10^{-9}$	$1.4\ 10^{-8}$	$2.5\ 10^{-8}$	$4.2\ 10^{-8}$
^{137}Cs	0	$3.2\ 10^{-11}$	$6.3\ 10^{-11}$	$9.5\ 10^{-11}$	$2.2\ 10^{-10}$	$9.4\ 10^{-10}$	$1.9\ 10^{-9}$	$2.8\ 10^{-9}$	$5.6\ 10^{-9}$	$1.1\ 10^{-8}$	$2.0\ 10^{-8}$
^{140}Ba	0	$3.2\ 10^{-11}$	$9.5\ 10^{-11}$	$1.8\ 10^{-10}$	$5.6\ 10^{-10}$	$1.9\ 10^{-9}$	$2.3\ 10^{-9}$	$2.4\ 10^{-9}$	$2.4\ 10^{-9}$	$2.4\ 10^{-9}$	$2.4\ 10^{-9}$
^{140}La	0	$1.0\ 10^{-10}$	$1.7\ 10^{-10}$	$2.1\ 10^{-10}$	$2.8\ 10^{-10}$	$3.0\ 10^{-10}$	$3.0\ 10^{-10}$	$3.0\ 10^{-10}$	$3.0\ 10^{-10}$	$3.0\ 10^{-10}$	$3.0\ 10^{-10}$
^{144}Ce	0	$2.6\ 10^{-12}$	$5.2\ 10^{-12}$	$7.8\ 10^{-12}$	$1.8\ 10^{-11}$	$7.5\ 10^{-11}$	$1.4\ 10^{-10}$	$2.1\ 10^{-10}$	$3.7\ 10^{-10}$	$6.0\ 10^{-10}$	$8.2\ 10^{-10}$

*The following radionuclides are assumed to be deposited in equilibrium with their decay products:
$^{106}Ru + {}^{106}Rh$, $^{137}Cs + {}^{137m}Ba$, $^{144}Ce + {}^{144}Pr$, $^{132}Te + {}^{132}I$.

TABLE 17 Deposited gamma dose location factors

Environment	Location factor
Multistorey building	0.01
Typical UK house	0.1
Outdoor urban environment	1
Outdoor rural environment	1

Modified formulations of equations 10 and 11 including an appropriate location factor, LF_{depgam}, are shown in equations 12 and 13.

$$EGDR_t = LF_{depgam} \times \sum_n (GD_n \times EDRF_{n,t}) \quad (12)$$

$$EGD_t = LF_{depgam} \times \sum_n (GD_n \times EDF_{n,t}) \quad (13)$$

where LF_{depgam} = external deposited gamma dose location factor for the particular situation

5.4.5 Resuspension of deposited radionuclides

The significance of this exposure pathway may be assessed by monitoring concentrations of radionuclides in air or, if no measurements are available, it may be estimated through the use of a resuspension model (Walsh, 2002). Equations 14 and 15 show the instantaneous and time integral of resuspended air concentration of a deposited radionuclide.

$$ACR_{n,t} = GD_n \times RCF_{n,t} \quad (14)$$

$$TIACR_{n,t} = GD_n \times RIF_{n,t} \quad (15)$$

where $ACR_{n,t}$ = resuspended concentration in air at time t of radionuclide, n (Bq m^{-3})

GD_n = initial level of ground deposition of radionuclide, n (Bq m^{-2})

$RCF_{n,t}$ = time-dependent resuspended air concentration factor for radionuclide (Bq m^{-3} per Bq m^{-2})

$TIACR_{n,t}$ = time integral, to time t, of resuspended concentration of radionuclide n in air (Bq s m^{-3})

$RIF_{n,t}$ = time-dependent resuspended (integral) air concentration factor for radionuclide n in air (Bq s m^{-3} per Bq m^{-2})

Inhalation of resuspended radionuclides is only significant for those radionuclides which do not present an external radiation hazard.

Table 18 shows levels of instantaneous and time-integrated (resuspended) air concentrations of radionuclides at various times arising from initial unit

deposition on the ground. Doses arising from inhalation of resuspended radionuclides may be assessed using equations 2 and 3.

TABLE 18 Resuspended air concentrations

(a) Instantaneous air concentration (Bq m^{-3} per Bq m^{-2})

Nuclide	Time						
	1 day	1 week	2 weeks	1 month	3 months	6 months	1 year
^{234}U	$1.2\ 10^{-6}$	$1.7\ 10^{-7}$	$8.\ 7\ 10^{-8}$	$4.1\ 10^{-8}$	$1.4\ 10^{-8}$	$7.7\ 10^{-9}$	$4.3\ 10^{-9}$
^{235}U	$1.2\ 10^{-6}$	$1.7\ 10^{-7}$	$8.7\ 10^{-8}$	$4.1\ 10^{-8}$	$1.4\ 10^{-8}$	$7.7\ 10^{-9}$	$4.3\ 10^{-9}$
^{238}U	$1.2\ 10^{-6}$	$1.7\ 10^{-7}$	$8.7\ 10^{-8}$	$4.1\ 10^{-8}$	$1.4\ 10^{-8}$	$7.7\ 10^{-9}$	$4.3\ 10^{-9}$
^{238}Pu	$1.2\ 10^{-6}$	$1.7\ 10^{-7}$	$8.7\ 10^{-8}$	$4.1\ 10^{-8}$	$1.4\ 10^{-8}$	$7.6\ 10^{-9}$	$4.3\ 10^{-9}$
^{239}Pu	$1.2\ 10^{-6}$	$1.7\ 10^{-7}$	$8.7\ 10^{-8}$	$4.1\ 10^{-8}$	$1.4\ 10^{-8}$	$7.7\ 10^{-9}$	$4.3\ 10^{-9}$
^{241}Pu	$1.2\ 10^{-6}$	$1.7\ 10^{-7}$	$8.7\ 10^{-8}$	$4.1\ 10^{-8}$	$1.4\ 10^{-8}$	$7.5\ 10^{-9}$	$4.1\ 10^{-9}$
^{241}Am	$1.2\ 10^{-6}$	$1.7\ 10^{-7}$	$8.7\ 10^{-8}$	$4.1\ 10^{-8}$	$1.4\ 10^{-8}$	$7.7\ 10^{-9}$	$4.3\ 10^{-9}$
^{242}Cm	$1.2\ 10^{-6}$	$1.7\ 10^{-7}$	$8.2\ 10^{-8}$	$3.6\ 10^{-8}$	$9.8\ 10^{-9}$	$3.6\ 10^{-9}$	$9.1\ 10^{-10}$
^{244}Cm	$1.2\ 10^{-6}$	$1.7\ 10^{-7}$	$8.7\ 10^{-8}$	$4.1\ 10^{-8}$	$1.4\ 10^{-8}$	$7.5\ 10^{-9}$	$4.1\ 10^{-9}$

TABLE 18 Resuspended air concentrations

(b) Time integral of air concentration (Bq s m^{-3} per Bq m^{-2})

Nuclide	Time						
	1 day	1 week	2 weeks	1 month	3 months	6 months	1 year
^{234}U	$1.0\ 10^{-1}$	$3.1\ 10^{-1}$	$3.9\ 10^{-1}$	$4.6\ 10^{-1}$	$5.7\ 10^{-1}$	$6.4\ 10^{-1}$	$7.2\ 10^{-1}$
^{235}U	$1.0\ 10^{-1}$	$3.1\ 10^{-1}$	$3.9\ 10^{-1}$	$4.6\ 10^{-1}$	$5.7\ 10^{-1}$	$6.4\ 10^{-1}$	$7.2\ 10^{-1}$
^{238}U	$1.0\ 10^{-1}$	$3.1\ 10^{-1}$	$3.9\ 10^{-1}$	$4.6\ 10^{-1}$	$5.7\ 10^{-1}$	$6.4\ 10^{-1}$	$7.2\ 10^{-1}$
^{238}Pu	$1.0\ 10^{-1}$	$3.1\ 10^{-1}$	$3.8\ 10^{-1}$	$4.6\ 10^{-1}$	$5.7\ 10^{-1}$	$6.4\ 10^{-1}$	$7.2\ 10^{-1}$
^{239}Pu	$1.0\ 10^{-1}$	$3.1\ 10^{-1}$	$3.9\ 10^{-1}$	$4.6\ 10^{-1}$	$5.7\ 10^{-1}$	$6.4\ 10^{-1}$	$7.2\ 10^{-1}$
^{241}Pu	$1.0\ 10^{-1}$	$3.1\ 10^{-1}$	$3.8\ 10^{-1}$	$4.6\ 10^{-1}$	$5.7\ 10^{-1}$	$6.4\ 10^{-1}$	$7.1\ 10^{-1}$
^{241}Am	$1.0\ 10^{-1}$	$3.1\ 10^{-1}$	$3.9\ 10^{-1}$	$4.6\ 10^{-1}$	$5.7\ 10^{-1}$	$6.4\ 10^{-1}$	$7.2\ 10^{-1}$
^{242}Cm	$1.0\ 10^{-1}$	$3.0\ 10^{-1}$	$3.7\ 10^{-1}$	$4.4\ 10^{-1}$	$5.4\ 10^{-1}$	$5.8\ 10^{-1}$	$6.0\ 10^{-1}$
^{244}Cm	$1.0\ 10^{-1}$	$3.1\ 10^{-1}$	$3.8\ 10^{-1}$	$4.6\ 10^{-1}$	$5.7\ 10^{-1}$	$6.4\ 10^{-1}$	$7.1\ 10^{-1}$

5.4.6 Radionuclide contamination in food and water

If foodstuffs are thought likely to be contaminated as a consequence of an accidental release of radionuclides, initial assessments relevant to food pathways are likely to focus on determining the extent over which contamination levels are expected to exceed the relevant food intervention level. In the early period following a release of mixed fission products, the foodstuffs most likely to be affected are milk and leafy green vegetables. Table 19 shows the peak concentration of radionuclides in these two foodstuffs following unit (1 Bq m^{-2}) deposition. Results were obtained from the NRPB FARMLAND foodchain model (Brown, J and Simmonds, J R, 1995). No data are presented for tritium since this is specifically excluded from the Council Food Intervention Level (CFIL) categories. Very short-lived radionuclides, ^{132}Te and ^{140}La, are excluded since these fall outside the scope of the CFIL radionuclide groups. Owing to its short half-life, ^{132}I is omitted. In practice, very-short-lived radionuclides would not be expected to influence decisions on food restrictions.

The peak concentration of radionuclides in milk may not occur until a few days after deposition. Table 19(a) shows the time following deposition at which the peak concentration in milk is estimated in FARMLAND where cows had been out in the fields at the time of release. For radionuclides deposited on to and transferred into unprepared leafy green vegetables, the peak concentration would be expected to be observed around the time of cessation of deposition. The time dependence of the concentration of radioisotopes of strontium, iodine and caesium in cows' milk is shown in Figure 8.

Table 19 also shows for each radionuclide the level of initial ground deposition which would be expected to lead to peak concentrations in the foodstuffs exceeding the relevant EC intervention level. This assumes that a single radionuclide is deposited. The regulations associated with the EC intervention levels require that the summed concentrations of radionuclides in the same group are compared with the relevant intervention level. The threshold deposition concentrations presented here should therefore be used with caution since more than one radionuclide within the same group may contribute significantly to the summed concentration.

TABLE 19 Radionuclide transfer to foodstuffs

(a) Milk

Nuclide	Peak concentration (Bq kg^{-1} per Bq m^{-2})	Time to reach peak (d)	Relevant CFIL (Bq kg^{-1})	Threshold deposit for exceeding CFIL (Bq m^{-2})
^{60}Co	$5.1\ 10^{-2}$	2	1000	$2.0\ 10^{4}$
^{89}Sr	$1.1\ 10^{-2}$	5	125	$1.1\ 10^{4}$
^{90}Sr	$1.2\ 10^{-2}$	5	125	$1.0\ 10^{4}$
^{95}Zr	$2.5\ 10^{-4}$	2	1000	$4.0\ 10^{6}$
^{95}Nb	$2.4\ 10^{-4}$	2	1000	$4.1\ 10^{6}$
^{103}Ru	$2.5\ 10^{-5}$	2	1000	$4.1\ 10^{7}$
^{106}Ru	$2.5\ 10^{-5}$	2	1000	$3.9\ 10^{7}$
^{131}I	$7.2\ 10^{-2}$	4	500	$7.0\ 10^{3}$
^{133}I	$1.4\ 10^{-2}$	2	500	$3.6\ 10^{4}$
^{135}I	$2.5\ 10^{-3}$	1	500	$2.0\ 10^{5}$
^{134}Cs	$7.2\ 10^{-2}$	5	1000	$1.4\ 10^{4}$
^{137}Cs	$7.2\ 10^{-2}$	5	1000	$1.4\ 10^{4}$
^{140}Ba	$1.1\ 10^{-2}$	2	1000	$8.8\ 10^{4}$
^{144}Ce	$5.0\ 10^{-4}$	2	1000	$2.0\ 10^{6}$
^{234}U	$1.5\ 10^{-2}$	2	1000	$6.6\ 10^{4}$
^{235}U	$1.5\ 10^{-2}$	2	1000	$6.6\ 10^{4}$
^{238}U	$1.5\ 10^{-2}$	2	1000	$6.6\ 10^{4}$
^{238}Pu	$1.0\ 10^{-6}$	7	20	$1.9\ 10^{7}$
^{239}Pu	$1.0\ 10^{-6}$	7	20	$1.9\ 10^{7}$
^{241}Pu	$1.0\ 10^{-6}$	7	1000	$1.0\ 10^{9}$
^{241}Am	$1.0\ 10^{-6}$	7	20	$1.9\ 10^{7}$
^{242}Cm	$1.0\ 10^{-6}$	6	20	$2.0\ 10^{7}$
^{244}Cm	$1.0\ 10^{-6}$	7	20	$1.9\ 10^{7}$

TABLE 19 Radionuclide transfer to foodstuffs

(b) Leafy green vegetables

Nuclide	Peak concentration (Bq kg^{-1} per Bq m^{-2})	Relevant CFIL (Bq kg^{-1})	Threshold deposit for exceeding CFIL (Bq m^{-2})
^{60}Co	0.3	1250	$4.2\ 10^3$
^{89}Sr	0.3	750	$2.5\ 10^3$
^{90}Sr	0.3	750	$2.5\ 10^3$
^{95}Zr	0.3	1250	$4.2\ 10^3$
^{95}Nb	0.3	1250	$4.2\ 10^3$
^{103}Ru	0.3	1250	$4.2\ 10^3$
^{106}Ru	0.3	1250	$4.2\ 10^3$
^{131}I	0.3	2000	$6.7\ 10^3$
^{133}I	0.3	2000	$6.7\ 10^3$
^{135}I	0.3	2000	$6.7\ 10^3$
^{134}Cs	0.3	1250	$4.2\ 10^3$
^{137}Cs	0.3	1250	$4.2\ 10^3$
^{140}Ba	0.3	1250	$4.2\ 10^3$
^{144}Ce	0.3	1250	$4.2\ 10^3$
^{234}U	0.3	1250	$4.2\ 10^3$
^{235}U	0.3	1250	$4.2\ 10^3$
^{238}U	0.3	1250	$4.2\ 10^3$
^{238}Pu	0.3	80	$2.7\ 10^2$
^{239}Pu	0.3	80	$2.7\ 10^2$
^{241}Pu	0.3	1250	$4.2\ 10^3$
^{241}Am	0.3	80	$2.7\ 10^2$
^{242}Cm	0.3	80	$2.7\ 10^2$
^{244}Cm	0.3	80	$2.7\ 10^2$

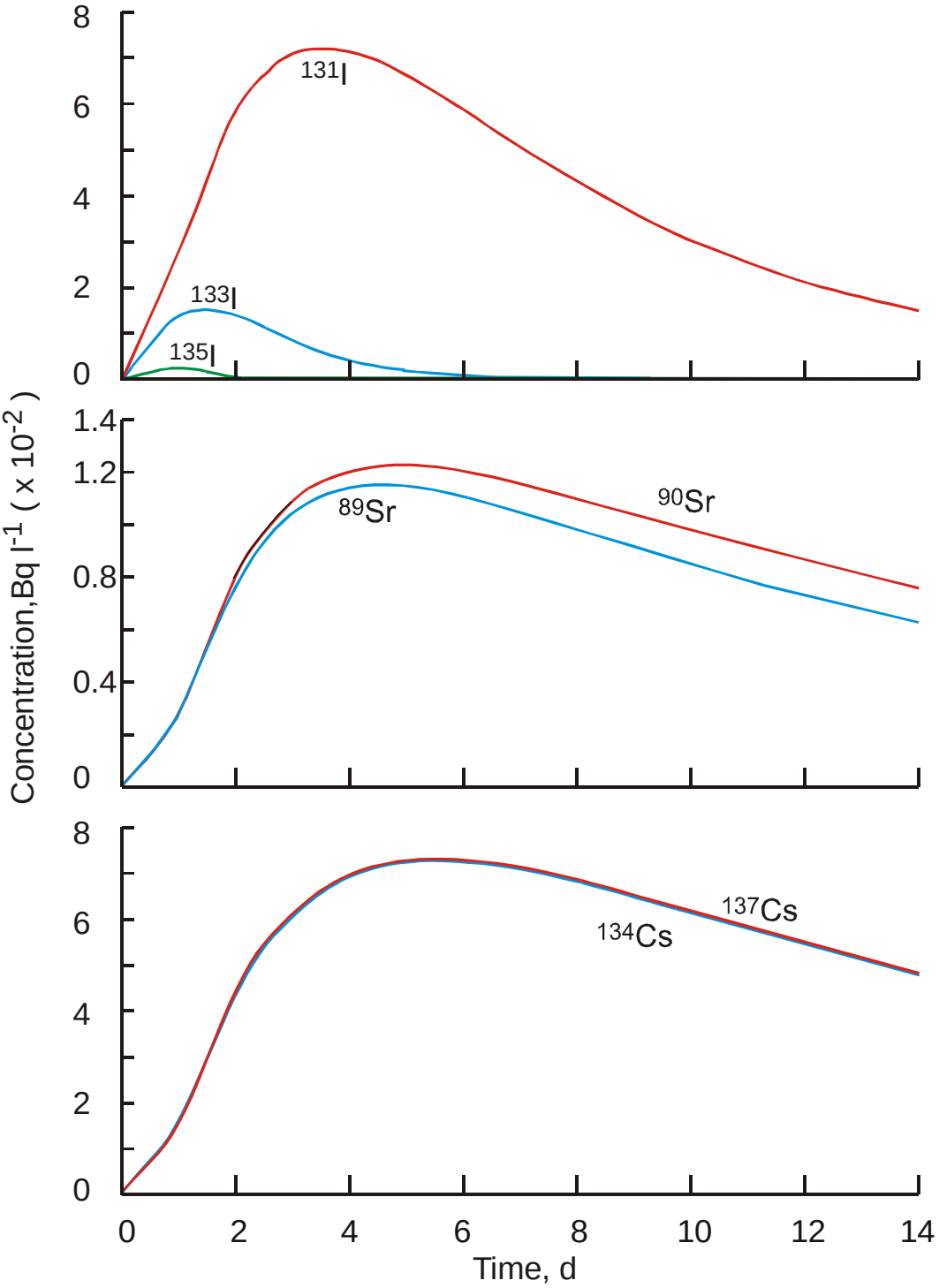


FIGURE 8 Time dependence of radionuclide concentration in milk

The peak radionuclide concentrations in food and their associated threshold deposition concentrations are based on a fixed pessimistic set of assumptions regarding the time of year at which the deposition occurs.

For leafy green vegetables, the peak concentrations shown in Table 19(b) exclude the significant reduction, typically 80% (Wilkins, B T, *et al*, 1987, in radionuclide contamination levels that would be expected to result from normal

food preparation activities such as removing outer leaves and rinsing the vegetables.

A number of other factors may affect the evolution of the concentration of radionuclides in various foodstuffs. An environmental sampling and analysis programme addressing the appropriate areas, foodstuffs, times of year, and radionuclides is likely to be required to make detailed decisions associated with contaminated foodstuffs.

NRPB has advised (NRPB, 1994) that the CFILs for liquid foodstuffs should be applied to drinking water supplies in the event of an accident. It is not possible to provide general information on what levels of deposition on to open water or surfaces might lead to the drinking water intervention levels being exceeded because such transfer is highly site specific and there is a large range of dilution and delay factors that might influence the concentration of radionuclides in drinking water. In the event of an accident, the most effective means of identifying whether drinking water supplies might be significantly contaminated would be through sampling and analysis of water contamination levels in areas which might be affected by radionuclide deposition and runoff.

6 ATMOSPHERIC DISPERSION

6.1 Introduction

This section discusses the atmospheric dispersion of radionuclides following an accidental release of radionuclides to atmosphere. It discusses the influences of weather, particularly wind speed and rainfall rate, arrangements for obtaining weather forecasts for the area surrounding the release, and estimation of the atmospheric stability category. A simple application of the straight-line Gaussian plume model is provided. This model allows estimates to be made of plume travel and downwind air concentrations. Radionuclide deposition under dry and wet conditions is also discussed.

The Gaussian model presented here is simple to apply and requires a minimum of input data but its scope of application is limited. In particular, it assumes flat terrain as well as static and uniform dispersion conditions. This is likely to be adequate for situations requiring assessments of likely conditions within a few tens of kilometres of a release point for a period of a few hours.

To estimate conditions beyond this scale, more sophisticated models are available which take account of the variation of dispersion conditions over time and space. Similarly, more sophisticated models may be required to incorporate terrain-related effects. Within the UK, models such as the Atmospheric Dispersion Modelling System (Carruthers, D J, *et al*, 1997) (ADMS) may be used to provide more sophisticated modelling of dispersion and deposition over short and medium ranges. The UK Meteorological Office NAME model (Maryon, R H and

Ryall, D B, 1996) is used within the RIMNET phase 2 system to model dispersion and deposition over larger geographical scales.

6.2 Weather

In order to track the plume and to use the data in this section, it is necessary to know the wind speed downwind of the site and the rate of rainfall, if any. If no better information is available, these parameters can be estimated from observations (Meterological Office, 1983) as indicated in Tables 20 and 21.

It should be noted that the highest rainfall rates are associated with showers, which seldom persist at full intensity in any one place; but showers may track the plume.

6.2.1 Weather forecasting during an emergency

Emergency plans maintained by nuclear operators and the UK Meteorological Office include arrangements for providing rapid reports of current and forecast meteorological conditions in the event of an emergency. These reports may be used to assist decisions on radiation monitoring and protective measures.

6.2.2 Estimation of atmospheric stability category

The degree of dispersion of the plume depends on the atmospheric stability category. There are seven categories (A–G), which can be determined from the wind speed, solar radiation and cloud cover (Clarke, R H, 1979). Figure 9 shows a flow chart for determining the stability category from observations.

6.3 Straight-line Gaussian plume model

A straight-line Gaussian plume model is often applied to model the short and medium range dispersion of radionuclides in the atmosphere. The main features of the model are given below.

6.3.1 Plume tracking

In order to estimate the track and spread of the plume, it is necessary to know the origin, the wind direction, the wind speed and the atmospheric stability category. It should be noted that estimates based on static dispersion conditions, although relatively simple to undertake, become increasingly unreliable when applied to periods longer than a few hours and distances greater than a few tens of kilometres.

TABLE 20 Wind speed

Description	Observation	Value	
		m s^{-1}*	km h^{-1}*
Calm	Smoke rises vertically	0.0–0.2	0–1
Light air	Smoke drifts; wind vanes do not move	0.3–1.5	1–6
Light breeze	Wind felt on face; leaves rustle	1.6–3.3	6–12
Gentle breeze	Leaves, small twigs move constantly; light flags extend	3.4–5.4	12–20
Moderate breeze	Dust, loose paper raised; small branches move	5.5–7.9	20–30
For wind speeds > 8 m s^{-1}, the atmospheric stability category is always D			
Fresh breeze	Small leafy trees sway	8–11	30–40
Strong breeze	Large branches sway; telephone wires whistle; trouble using umbrella	11–14	40–50
Near gale	Whole trees sway; hard to walk against wind	14–17	50–60
Gale	Twigs break off; progress generally impeded	17–21	60–75
Strong gale	Chimney pots and roof tiles removed	21–25	75– 90
Storm	Trees uprooted; much structural damage	25–28	90–100

* In round figures.

TABLE 21 Rainfall rate

Description	Observation	Value (mm h^{-1})
Slight to moderate drizzle	Windows and roads stream with moisture	<0.5
Heavy drizzle	Impairs visibility	0.5–1
Slight rain	Scattered large drops or more smaller drops; puddles form slowly	<0.5
Moderate rain	Puddles form quickly; some spray on hard surfaces	0.5–4
Heavy rain	Roaring on roofs; high splashing	>4
Slight shower	Scattered drops; puddles form	<2
Moderate shower	Puddles form quickly	2–10
Heavy shower	Roaring on roofs; visibility impaired	10–50

6.3.1.1 Plume spread

The model assumes that the downwind air concentration has a Gaussian cross-section (Jones, J A and Charles, D, 1982). Its spread on each side of the central axis is characterised by the parameter σ_y, which is a function of atmospheric stability category and is roughly proportional to the distance downwind from the origin (Figure 10). Taking the axial air concentration as 100%, the 50% contours are at $\pm 1.2\sigma_y$, and the 10% contours at $\pm 2.1\sigma_y$. Figure 11 shows plume spread for short releases in the different stability categories.

6.3.1.2 Off-axis corrections

If the location of interest is not on the plume centreline, the airborne and deposited concentrations of radionuclides will be reduced. Off-axis concentrations may be estimated by identifying the lateral off-axis distance (in metres) and dividing this by σ_y for the appropriate downwind distance and stability category (see Figure 12).

If this quotient is less than 0.5, the location is sufficiently close to the plume centreline that no correction is justified. Otherwise, the off-axis correction factor may be identified on Figure 12 and multiplied by the on-axis values to obtain an estimate of the concentration at the off-axis location.

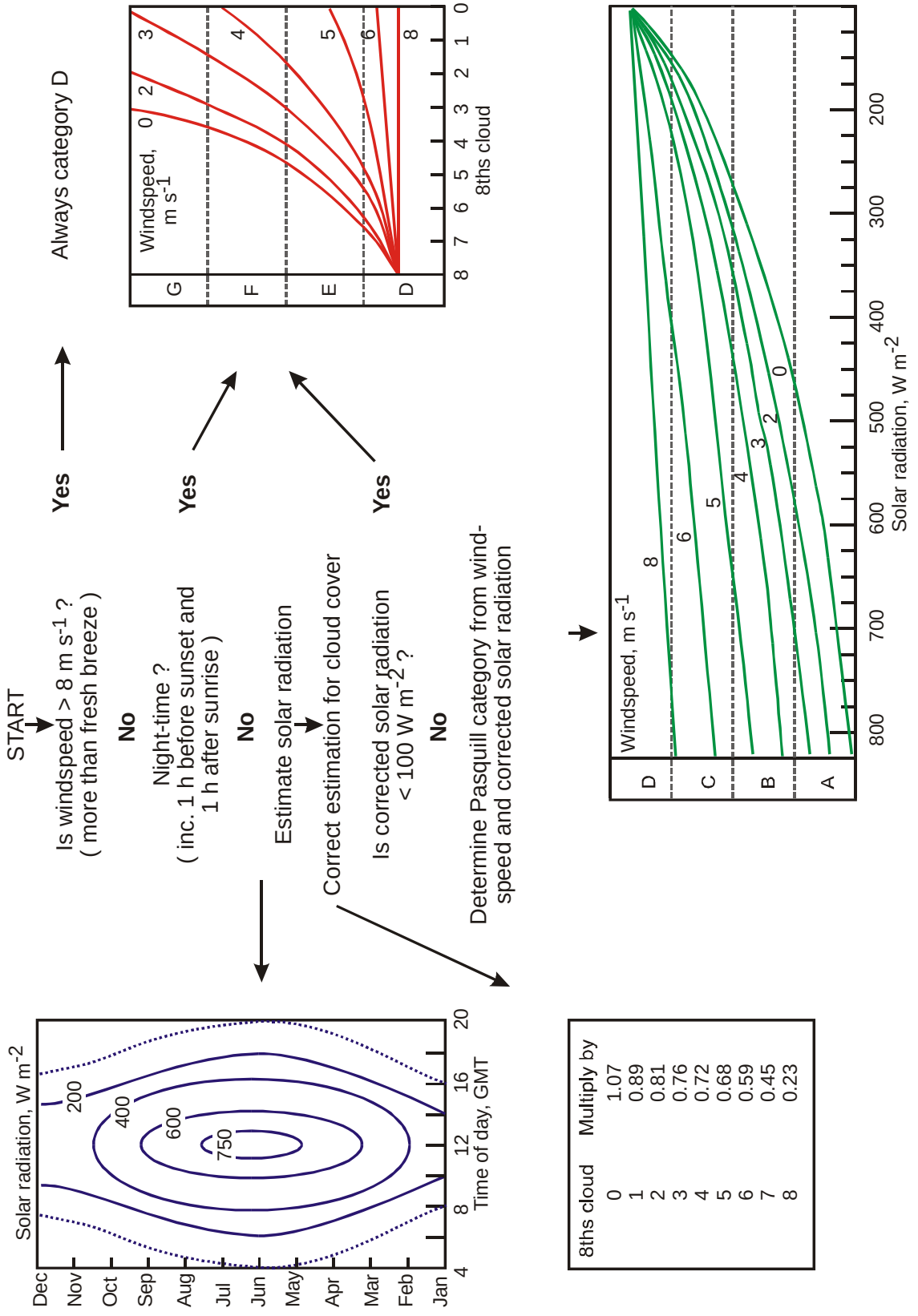


FIGURE 9 Estimation of Pasquill category from wind speed, solar radiation and cloud cover

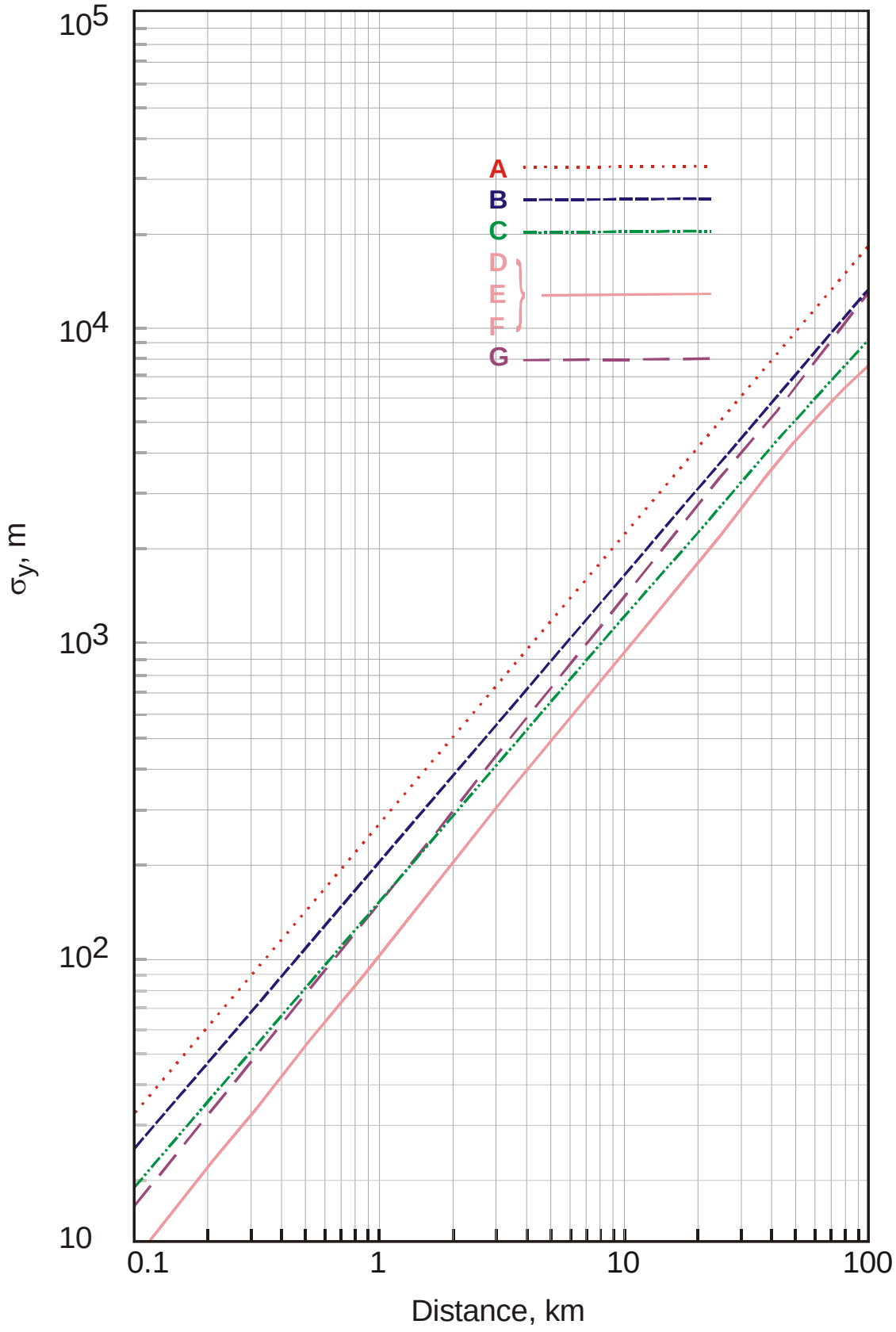


FIGURE 10 Horizontal standard deviation, σ_y, for a release of 30 minutes duration in each Pasquill stability category

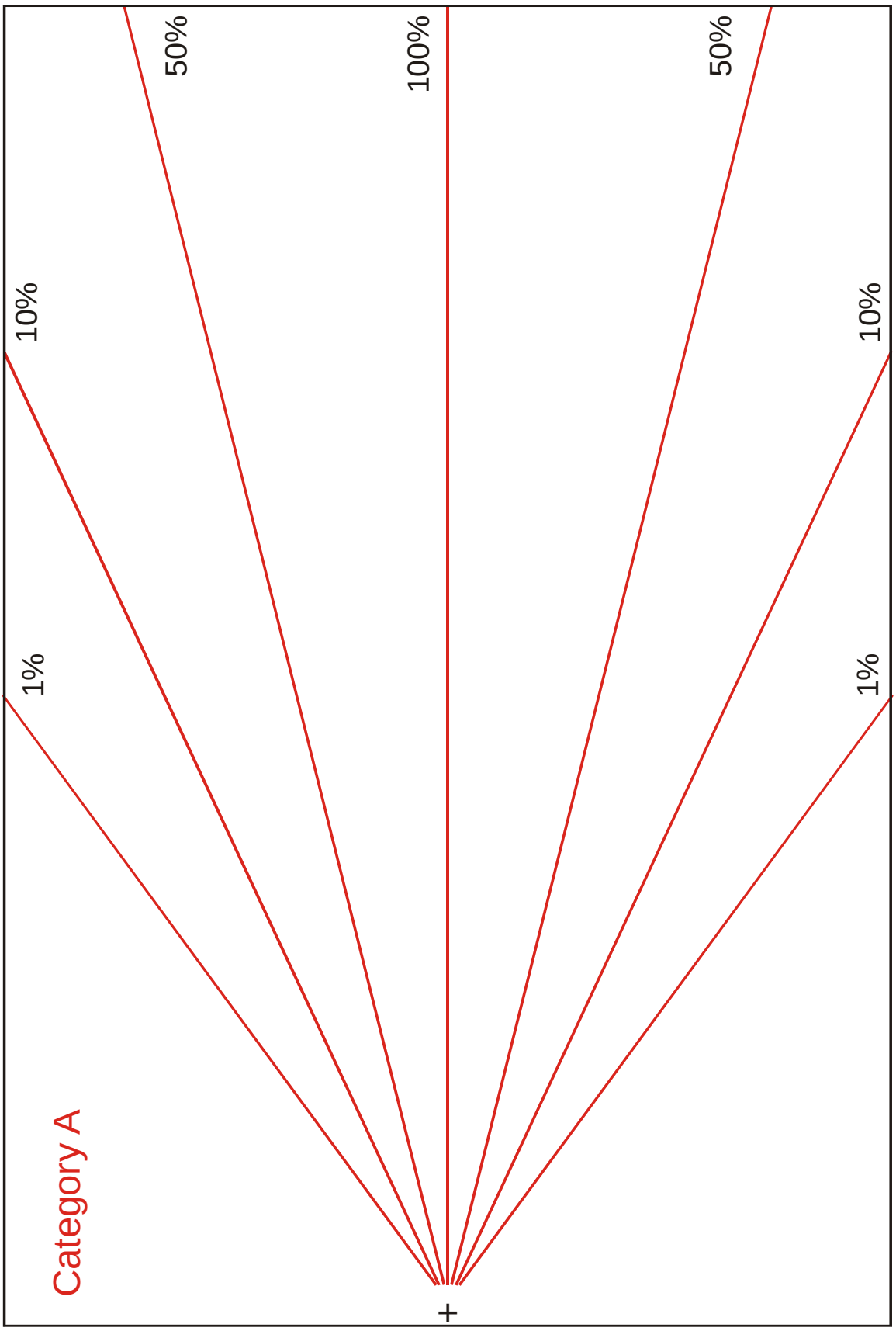


FIGURE 11(a) Plume spread in category A (short release)

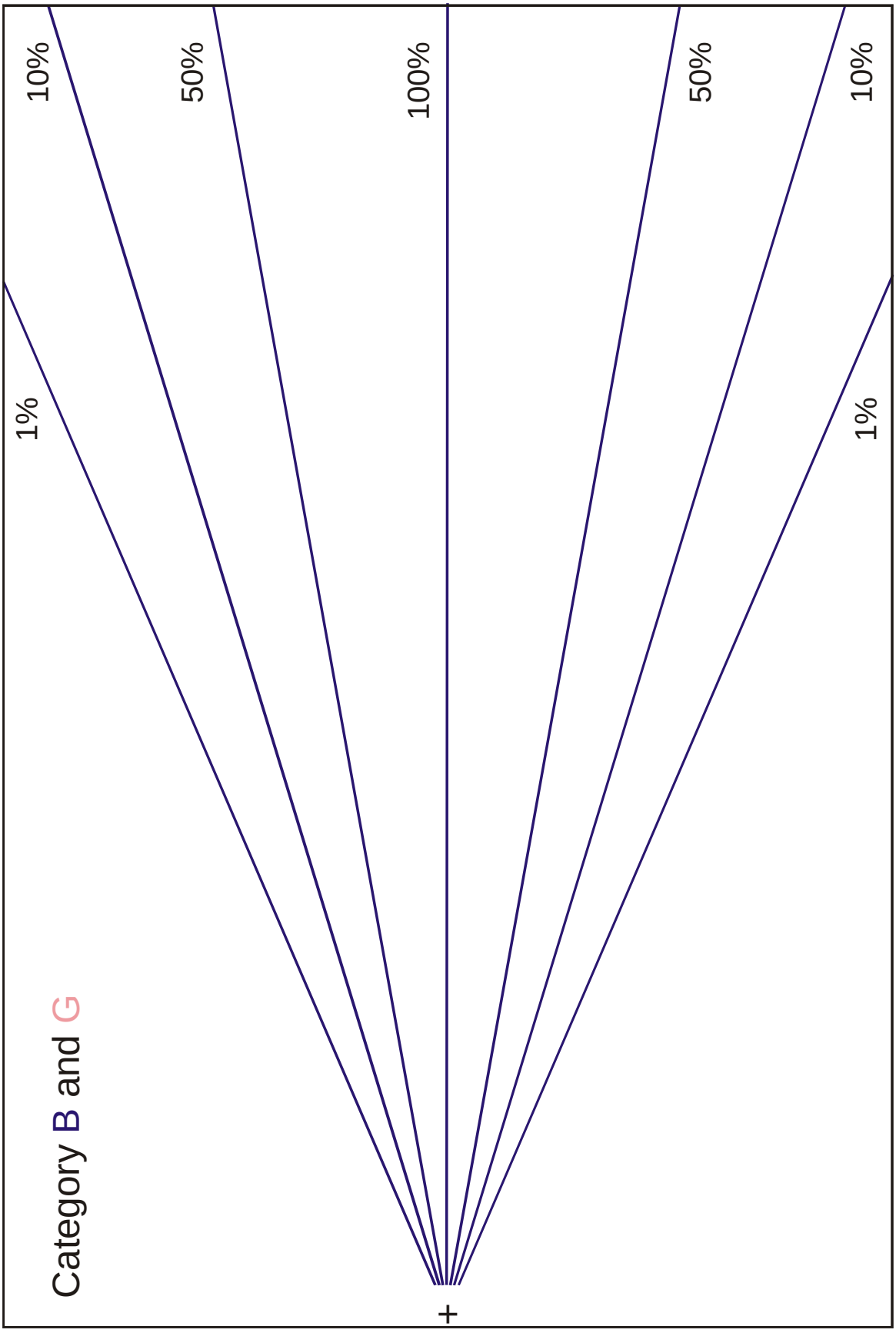


FIGURE 11(b) Plume spread in categories B and G (short release)

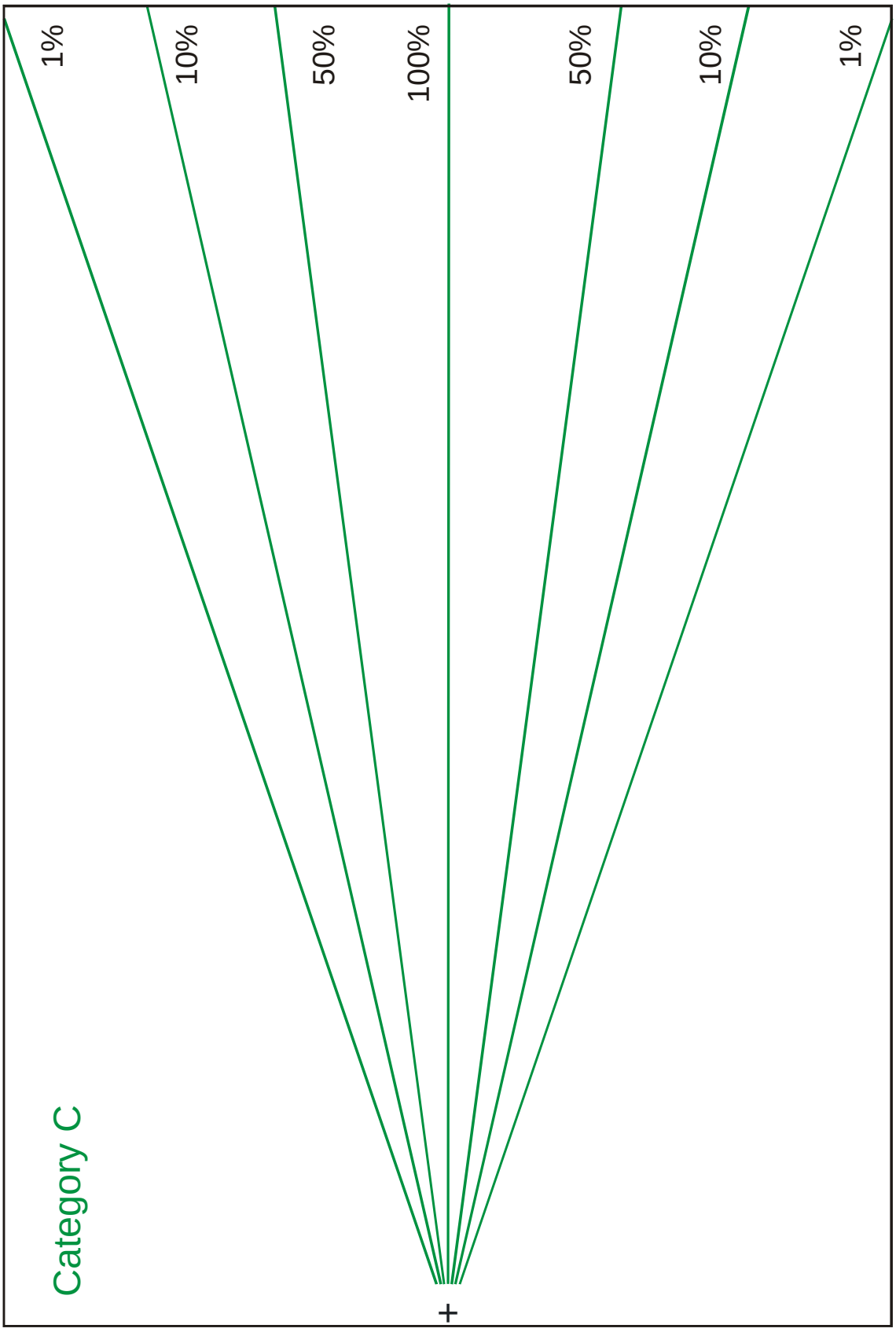


FIGURE 11(c) Plume spread in category C (short release)

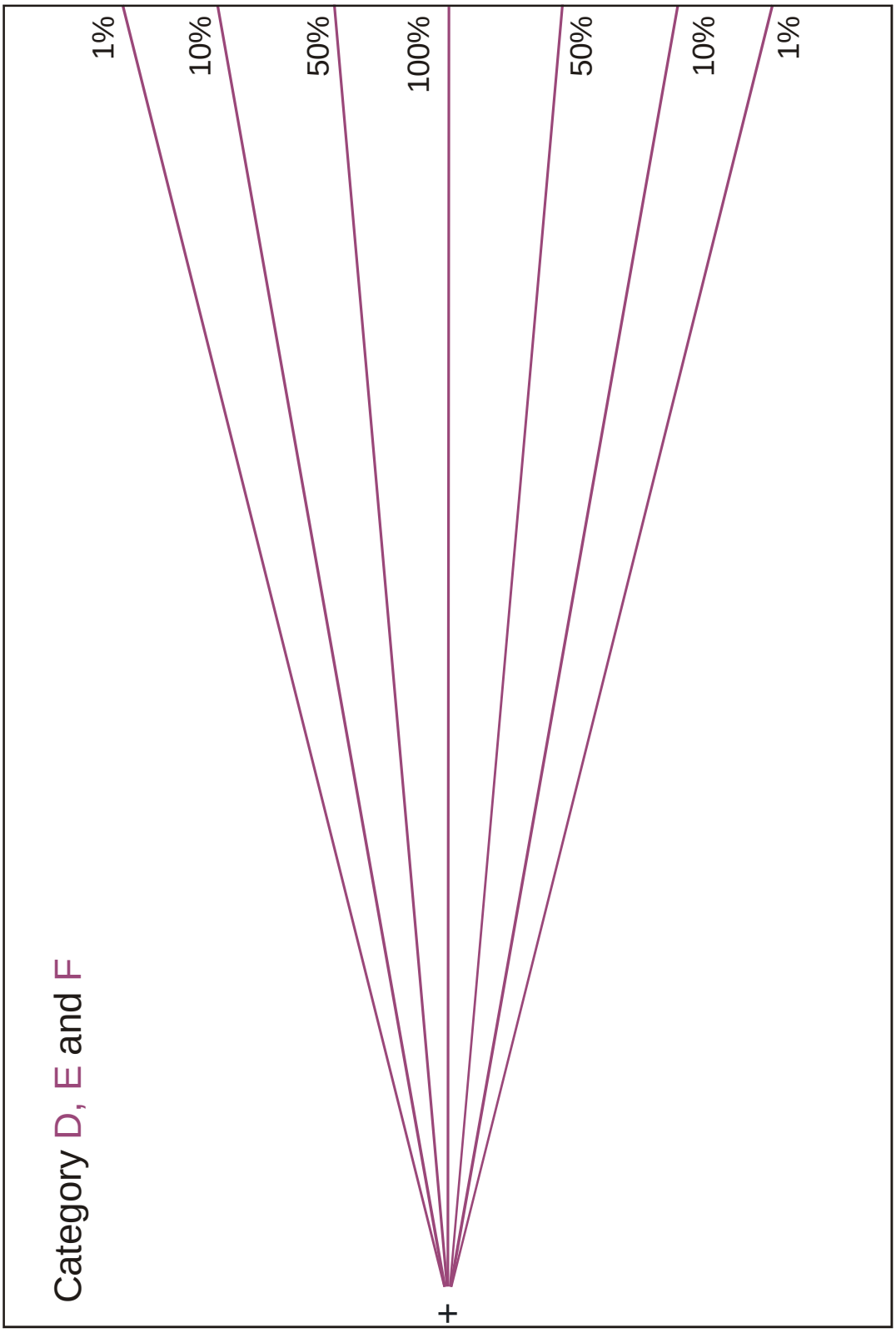


FIGURE 11(d) Plume spread in categories D, E and F (short release)

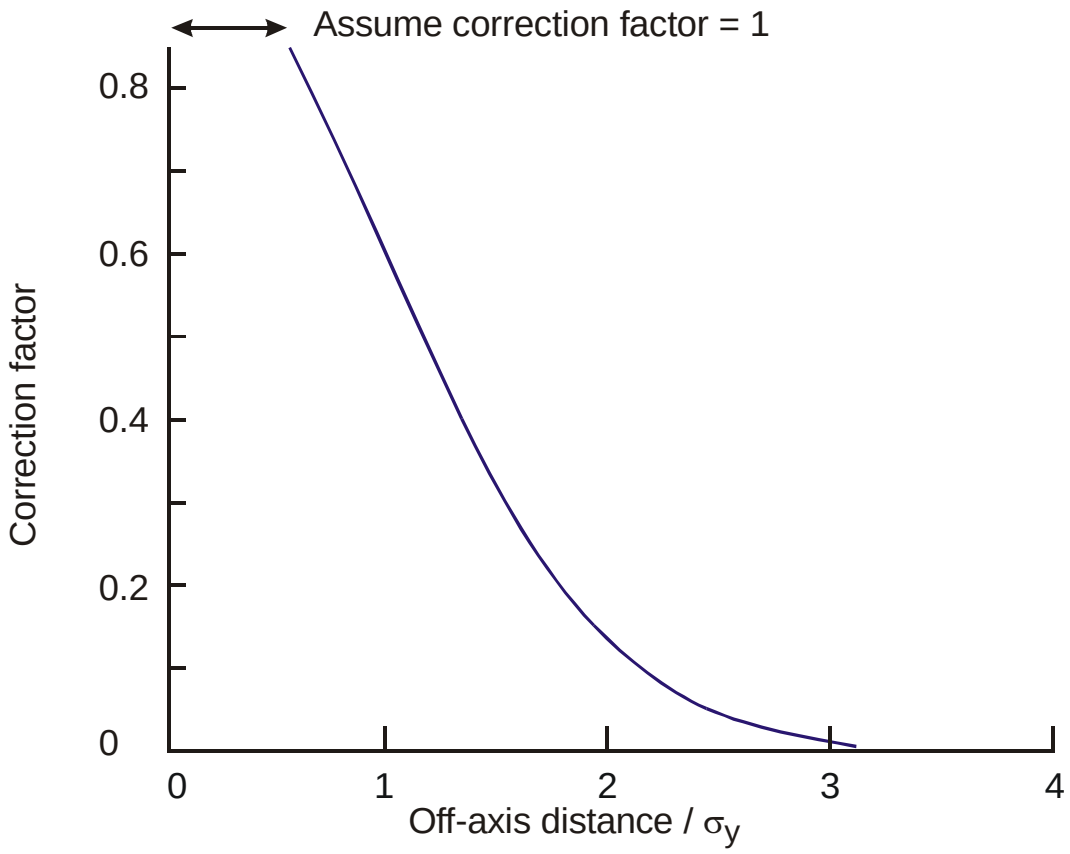


FIGURE 12 Off-axis correction factor (short release)

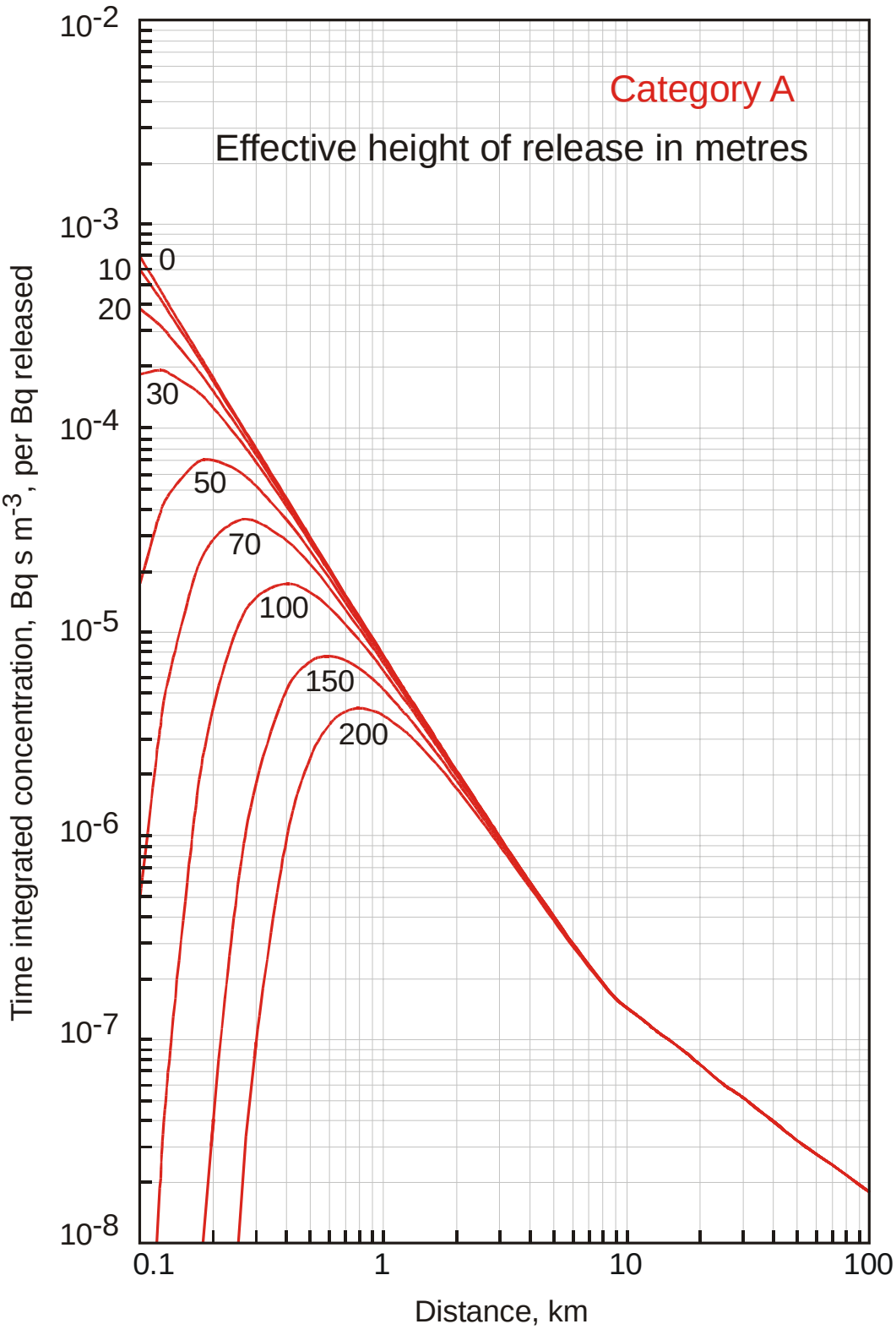


FIGURE 13(a) On-axis ground-level time-integrated concentrations as a function of effective release height for a short (30 minute) release – category A

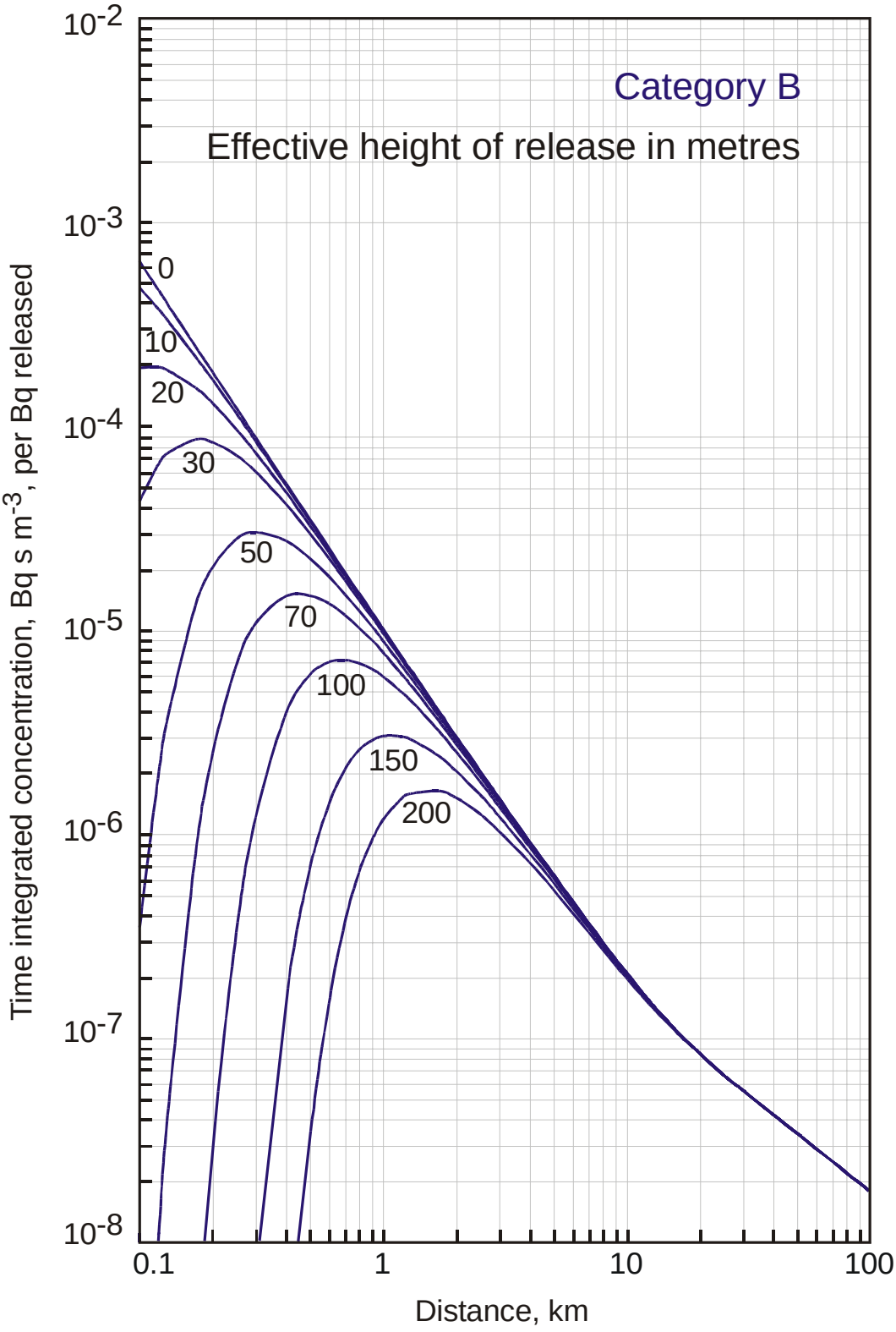


FIGURE 13(b) On-axis ground-level time-integrated concentrations as a function of effective release height for a short (30 minute) release – category B

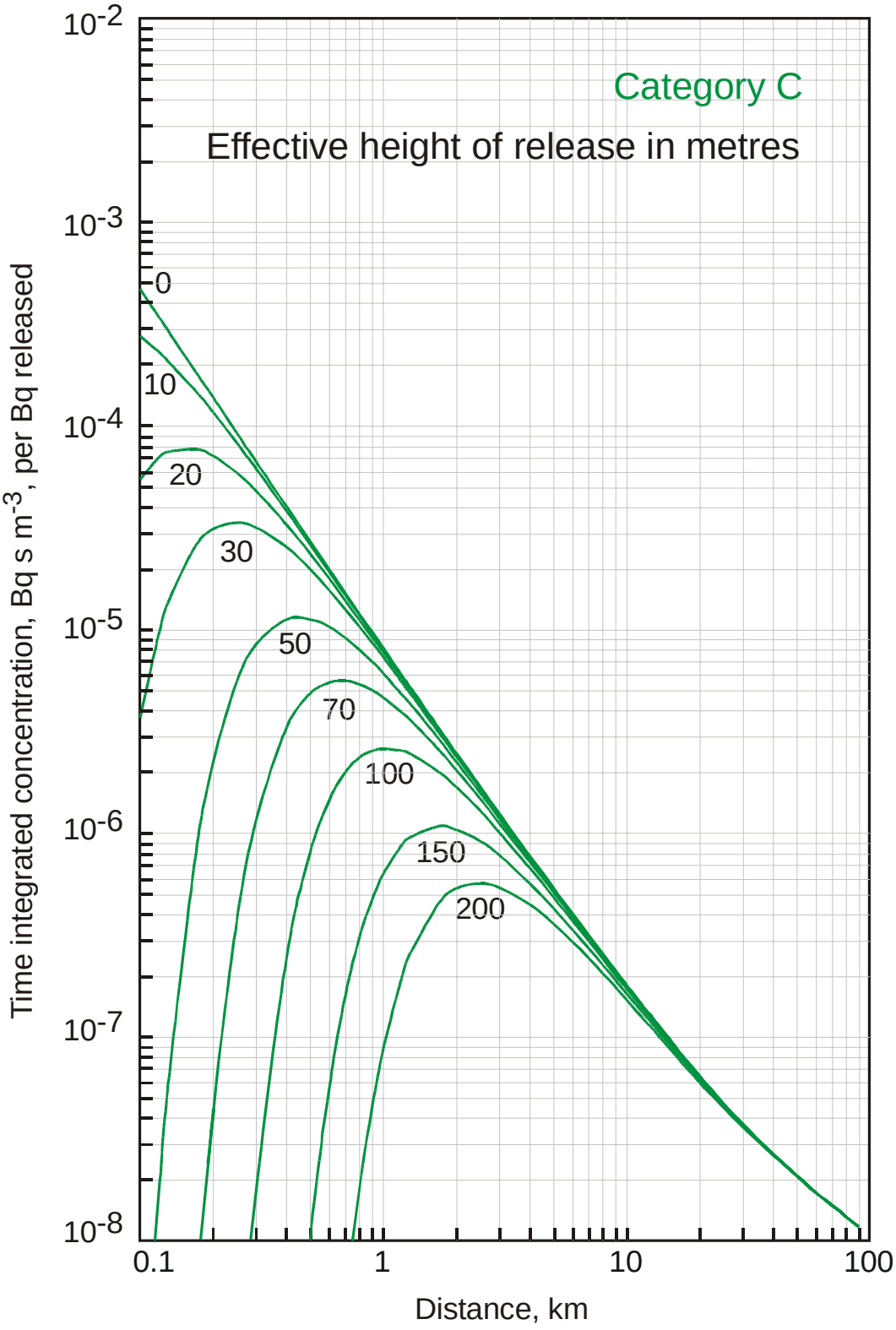


FIGURE 13(c) On-axis ground-level time-integrated concentrations as a function of effective release height for a short (30 minute) release – category C

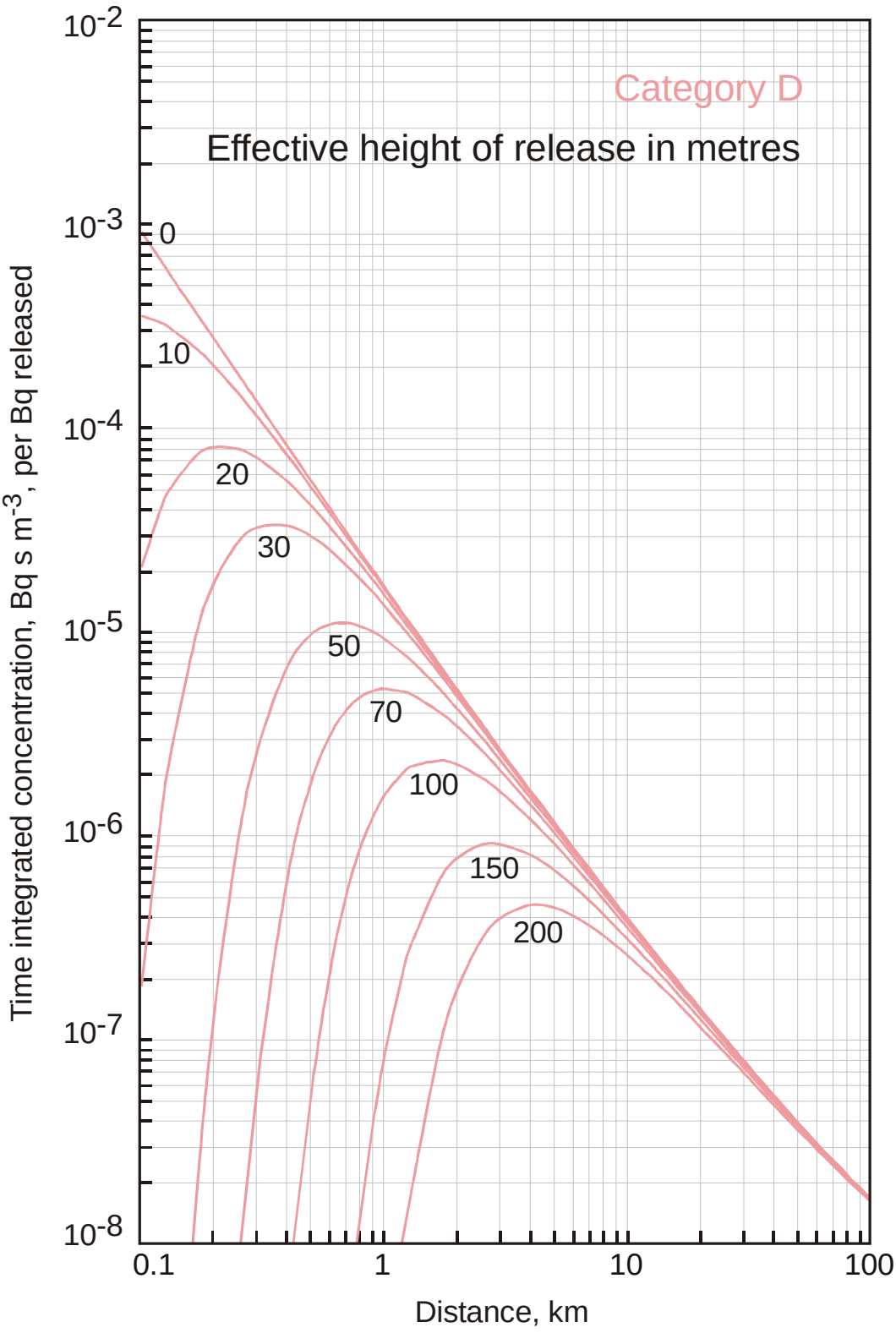


FIGURE 13(d) On-axis ground-level time-integrated concentrations as a function of effective release height for a short (30 minute) release – category D

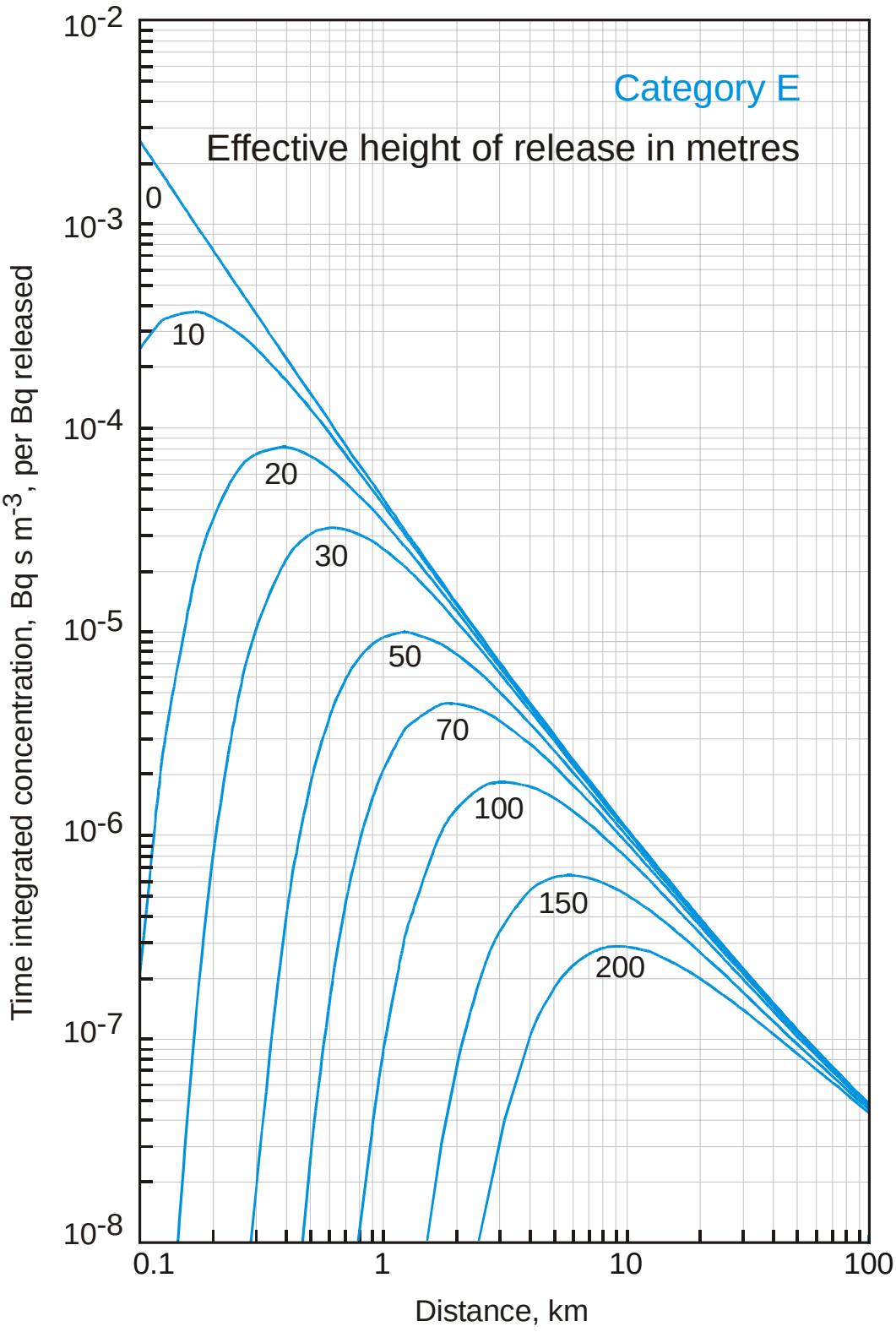


FIGURE 13(e) On-axis ground-level time-integrated concentrations as a function of effective release height for a short (30 minute) release – category E

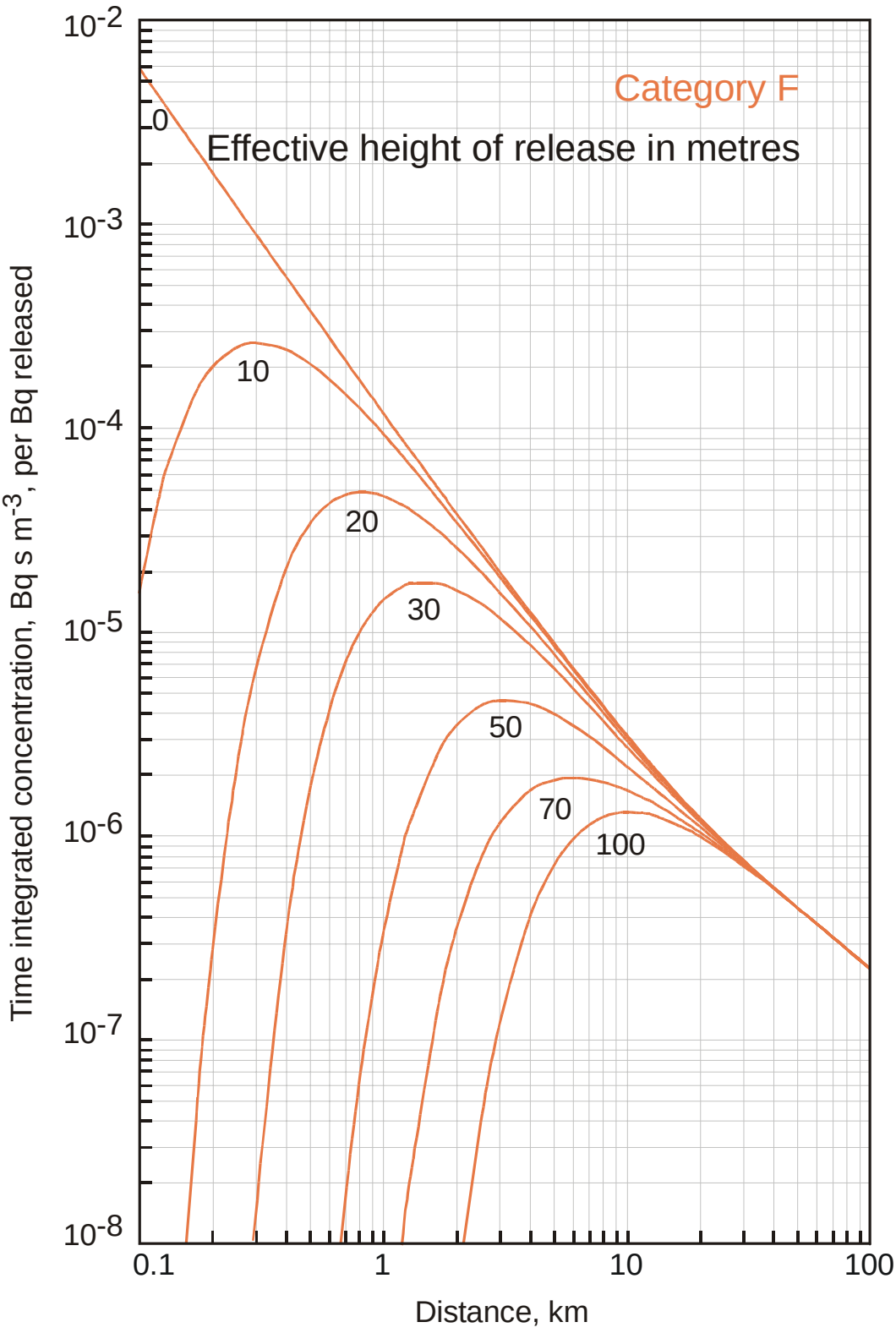


FIGURE 13(f) On-axis ground-level time-integrated concentrations as a function of effective release height for a short (30 minute) release – category F

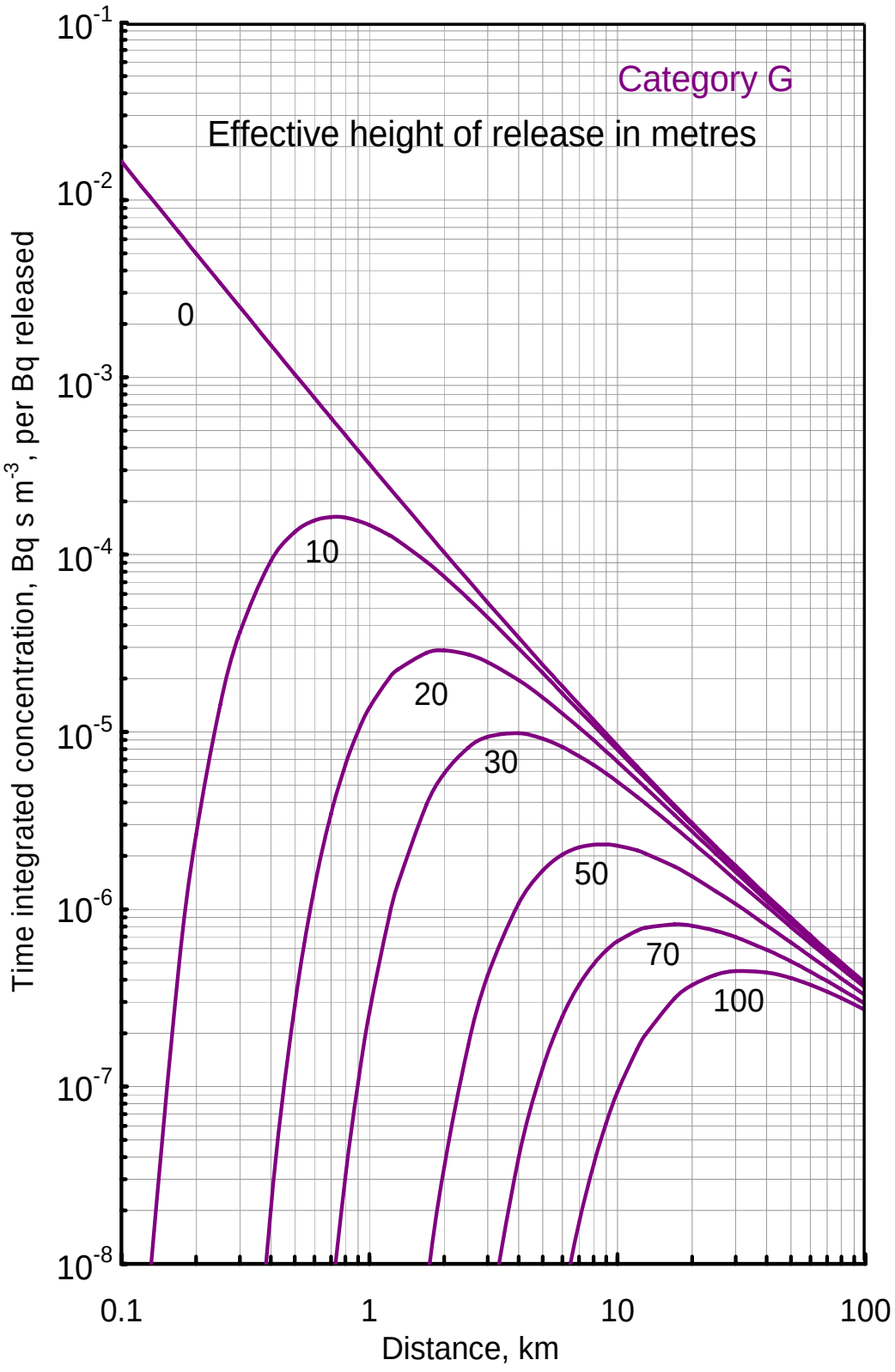


FIGURE 13(g) On-axis ground-level time-integrated concentrations as a function of effective release height for a short (30 minute) release – category G

6.3.2 Air concentrations

6.3.2.1 Time-integrated air concentrations

Time-integrated air concentrations for unit release (1 Bq), as a function of distance under different atmospheric stability categories, are given in Figure 13(a)–(g) (Jones, 1983). Air concentrations are given at ground level along the axis of the plume.

6.3.2.2 Long distances

The straight-line Gaussian plume model is valid only if prevailing atmospheric conditions persist. In practice, this usually restricts the range to a few tens of kilometres. Figure 13 should therefore only normally be used for distances up to a few tens of kilometres. Any further extrapolations should be made with caution.

6.3.2.3 Long releases

For releases longer than 30 minutes, the axial air concentrations may be multiplied by the factors given in Table 22. These correction factors assume that stability conditions remain constant throughout the period.

TABLE 22 Correction factors

Stability category	Release duration (h)					
	1	2	4	6	9	12
A	0.9	0.7	0.6	0.5	0.4	0.3
B	0.9	0.7	0.5	0.5	0.4	0.3
C	0.9	0.7	0.6	0.5	0.4	0.4
D	0.8	0.7	0.5	0.4	0.3	0.3
E	0.8	0.6	0.4	0.3	0.3	0.2
F	0.7	0.5	0.4	0.3	0.3	0.2
G	0.7	0.5	0.4	0.3	0.2	0.2

6.4 Deposition from the plume

6.4.1 Dry deposition

In the absence of measurements of deposition, the total dry deposit of a given radionuclide at a given place may be estimated as follows (Jones, J A and Charles, D, 1982; Jones, J A, 1983).

$$DD_n = TIAC_n \times Vg_n$$

where DD_n = concentration of radionuclide n on the ground (Bq m^{-2})

$TIAC_n$ = time-integrated concentration of radionuclide n in air (Bq s m^{-3})

Vg_n = dry deposition velocity of radionuclide n (m s^{-1})

The deposition velocity will be the same for all isotopes of the same chemical element, although it will depend on the chemical form, and hence on the nature of the accident. It will also depend on the type of surface on to which the activity is deposited. Dry deposition velocities are recognised to be very uncertain.

Depending on the circumstances, the uncertainty may be at least an order of magnitude, possibly even two or three. For rapid calculations in an emergency, the following values of deposition velocity are most commonly used.

10^{-2} m s^{-1} for reactive gases, eg inorganic iodine vapour

10^{-3} m s^{-1} for most nuclides in particulate form

10^{-5} m s^{-1} for gaseous organic forms of iodine

zero' for noble gases

The above calculation assumes no depletion of the plume. At ranges up to several kilometres, depletion by dry deposition is usually negligible.

Since there are considerable uncertainties in the values of dry deposition velocities, direct measurement of dry deposition should be made wherever possible.

Given measurement of ground (dry) deposition at a known on-axis downwind distance, dry deposition at other on-axis distances can be estimated directly by scaling from the dispersion graph for the appropriate atmospheric stability category (Figure 13). Deposition at off-axis locations can be estimated through the use of off-axis correction factors described above for use in estimating off-axis air concentrations.

6.4.2 Wet deposition

Order-of-magnitude estimates of the total wet deposition at a given place can be made as a guide to contingency planning, with the aid of the following formula (Jones, 1983):

$$WD_n = \frac{R_n \times FT}{WS \times D} \times 1.5 10^{-3} s^{-1}$$

where WD_n = total wet deposition of radionuclide n (Bq m^{-2})

R_n = release of radionuclide n (Bq)

FT = fraction of time for which it was raining while the plume was passing overhead

WS = wind speed (m s^{-1})

D = downwind axial distance (m)

This formula for wet deposition is derived from the formula given by Jones (Jones, 1983), assuming that there is no prior depletion of the plume, the atmospheric stability category is D, and the wet removal coefficient is 3 10^{-4} s^{-1}, which is an appropriate value for a rainfall rate of about 1 mm h^{-1} (moderate rain or slight showers).

Radionuclide deposition during precipitation can be many times greater than that under dry conditions and can show much more local variation. The formula

above is very approximate, although it should be conservative in most cases, possible exceptions being heavy showers and thunderstorms (Jones, J A, 1985). Calculations of this type are indicative only and should be supplemented by direct measurements wherever possible.

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